DELHI POLYTECHNIC
LIBRARY

CLASS NO......621.312............

BOOK NO....M. 42. P.................

ACCESSION NO..19279.........

POWER CAPACITORS

WESTINGHOUSE McGRAW-HILL ENGINEERING BOOKS FOR INDUSTRY

GIBBS—*Transformer Principles and Practice* (2*d ed.*)
GODSEY and YOUNG—*Gas Turbines for Aircraft*
MARBURY—*Power Capacitors*

PREVIOUSLY PUBLISHED McGRAW-HILL BOOKS BY WESTINGHOUSE AUTHORS

HALL—*Industrial Applications of Infrared*
JAMES and MARKLE—*Controllers for Electric Motors*
VEINOTT—*Fractional Horsepower Electric Motors* (2*d ed.*)
WAGNER and EVANS—*Symmetrical Components*

POWER CAPACITORS

BY R. E. MARBURY

Westinghouse Electric Corporation

FIRST EDITION

New York, Toronto, London
McGRAW-HILL BOOK COMPANY, INC.
1949

POWER CAPACITORS

Copyright, 1949, by the McGraw-Hill Book Company, Inc. Printed in the United States of America. All rights reserved. This book, or parts thereof, may not be reproduced in any form without permission of the publishers.

PREFACE

The use of capacitors on power circuits started in the United States about thirty years ago and has grown rapidly during the past ten years. It is not the intention of this book to deal with the detail of the design and manufacture of capacitors or to cover the entire field of capacitor applications and types of capacitors. The author's chief intent is to deal with the so-called power capacitors, meaning relatively large capacitor units and assemblies such as are used on power systems.

Application of capacitors to power systems involves numerous problems, the solution of which may be found in most engineering textbooks and in professional- and trade-journal articles that have appeared throughout the past twenty-five years or more. The author's purpose is to consolidate most of this information into a convenient form for use by those whose work brings them into contact with capacitor applications.

The author wishes to acknowledge his indebtedness to his associates in the Westinghouse Electric Corporation, as he has drawn freely on material prepared by them.

R. E. Marbury

East Pittsburgh, Pa.
February, 1949

CONTENTS

Preface v

Introduction ix

1. Capacitor Materials and Characteristics 1
2. Capacitor Rating, Design, and Manufacture 21
3. Industrial, High-frequency, and D-c Power Capacitors 46
4. Application of Shunt Capacitors to Industrial Power Circuits 64
5. Application of Shunt Capacitors to Utility Systems 89
6. Fuses, Switches, and Connections Used with Shunt Capacitors 113
7. Automatic Control of Capacitor Kvar 133
8. Series Capacitors for Line-reactance Compensations 155
9. Series Capacitors Directly Applied to Specific Industrial Loads 178
10. Capacitor Installation and Maintenance 190

Index 203

INTRODUCTION

The use of capacitors on power circuits first became a general practice about twenty-five years ago. For a long time they were used to a very limited extent to supply reactive kilovolt-amperes to loads in industrial plants where the power factor was very low and where extraordinary savings in power billing were possible through power-factor improvement.

A few electric utilities recognized the merits of installing capacitors near the loads and developed rates that provided an attractive return to the power user for improvement in power factor. Other utilities developed similar rate incentives. The rates for electric power offered then by most utilities eventually contained features that took power factor into account, and the installation cost of capacitors at or near the loads could be recovered in 6 months to 3 years. The wide variation in savings resulting from the installation of capacitors was in part due to variations in power-system economics.

The growing demand for power capacitors supported constant development by the manufacturers and continued search for improved materials with which to build them. Many of the early installations of capacitors were not highly successful, because the art had not advanced to a point where reliable designs could be produced at a cost that economically justified their use. Advances in materials, processes, and construction made possible more efficient designs and at the same time lower costs per kvar. As this trend continued, the field for capacitors broadened at an increasing rate.

The first advance came through stressing cost reduction and reliability rather than size and weight, by taking advantage of the cost of material relative to thickness, and by designing for maximum safety factor per dollar invested in available dielectric materials. This resulted in a capacitor that had less kvar per unit of weight but which gave dependable service. This approach was discussed by the author in a paper entitled "Recent Advances in the Design, Manufacturing and Testing of Static Condensers in Power Sizes," presented at the Midwinter Convention of the A.I.E.E. in Philadelphia in February, 1924.

In the period from 1924 to the present, improvements have taken place in paper, foil, impregnants, terminal design, processing, and testing, so that the capacitors made to date are only about one-tenth as large and costly per kvar.

The advantage of power-factor improvement or the need for it varies with the industry according to the size and types of motors used and the conditions under which they are operated. Activities such as the rubber and the nonferrous-metals industries operate with relatively high power factors because of the large number of synchronous motors and the general operating conditions, while the textile industry and others using a large number of small motors usually have much lower average power factors.

If the need for power-factor improvement in industrial plants is considered on a relative basis, it will be found that of all the reactive current required for industrial loads the textile industry would require about 22 per cent, the food industry 19 per cent, and the machinery industry 15 per cent, with the remaining 44 per cent distributed over all other industries.

In 1936 the utilities became interested in capacitors as a means of greatly improving the operation of distribution circuits. Distribution of capacitors over these circuits made possible considerable increase in the salable power that could be transmitted, and improved the service that could be rendered from the viewpoint of voltage regulation. Also the power factor of many small industrial and residential loads could be improved much more economically than by applying capacitors individually to these loads and financing their purchase through power-rate incentives. This trend was augmented by the development of new capacitor designs particularly suited to application on distribution circuits.

Since 1941 utilities have extended the use of capacitors to large blocks of 10,000 kvar or more located at substations. These are used alone, or in conjunction with synchronous condensers, for supplying reactive kvar to large segments of the distribution system and controlling voltage. The released system capacity is generally worth many times the cost of the capacitors required, and because of this the use of capacitors in this manner has been quite general. The reduced first cost, losses, attendance, and maintenance, compared with synchronous condensers, make this a very attractive solution of the load-reactive problem. The fact that individual installations can be made as small as desired with very little increase in cost per kvar permits selection of sizes and locations to the best advantage in releasing system capacity.

Throughout the development and growing use of shunt capacitors it has always been recognized that they could be placed in series with the line and thus compensate for line reactance, thereby reducing voltage dips caused by fluctuating loads. Also, the power-transmitting limits of the line could be greatly improved. Capacitors may also be used in series with loads under certain conditions with very beneficial results; in this case the loads or device and the series capacitor must be treated as one piece of equipment. An example of this is the resistance welder with its series capacitor.

While series capacitors have been installed occasionally over the past 15 years or more, it is only during the last 10 years that serious consideration has been given to large series capacitors. The first installation of a series capacitor on a 66-kv line was in 1947, and the results were very gratifying. Installations of other large series capacitors are under consideration. As transmission distances increase, the line reactance becomes a problem. To continue increasing the transmitted voltage rapidly increases line costs. For very long distances, power-limit or stability considerations and load and line kvar requirements tend to increase unit power costs rapidly. The possibility of using series-connected capacitors to compensate for line reactance of long transmission lines will therefore receive a great deal of consideration.

By 1928 the total kvar of power capacitors installed in the United States probably did not exceed 300,000. Ten years later it had reached 1,400,000. By the end of 1943 the total installed kvar was at least 5,000,000. Today there are more than 13,000,000 kvar of capacitors in use, of which an estimated 6,000,000 are installed directly on utility circuits.

Prior to 1932 all large power capacitors were made with mineral oil as an impregnant. The use of chlorinated aromatic hydrocarbon compounds for paper impregnation, together with other advances in the art, brought about great improvements in reduced cost, size, and weight. Today capacitor units weigh less than 14 per cent of what they did back in 1924, and the volume reduction per kvar is of the same order. This reduction is an important factor in the growing popularity of the pole-mounted installations that predominate in utility applications.

As large power-capacitor units became available, the same basic designs and parts provided ratings for direct-current applications and applications for power-factor improvement at high frequencies. Capacitors may be used as reservoirs to store energy and thus serve as brief power supplies. They can become balance wheels and supply rhythmic impulses and may be used as valves to pass alternating current and block direct current. Their low internal resistance and inductance combined with their energy absorption capacity make them useful in *suppressing arcs, protecting equipment against steep wave-front surges, and producing a large flow of current in many industrial processes.*

Although, during the first half of the century, the principal use of large capacitors has been for the improvement of power factor, similar capacitors are being used increasingly in many other applications. During the next few years, they will be used for storing large quantities of energy for the purpose of producing intense cathode rays. They will also be used for storing energy to be used in welding, operation of gas-filled lights for airport lighting, snapshot X rays, and numerous pieces of equipment associated with atomic research and perhaps commercial equipment resulting from such research. Many of these capacitors utilize the same materials, processes, and parts as 60-cycle power capacitors, and for this reason they are included in the scope of this book.

CHAPTER 1

CAPACITOR MATERIALS AND CHARACTERISTICS

STATIC-ENERGY STORAGE

When a voltage is applied to an insulating medium, such as air, separating two metal surfaces, electrostatic energy is stored in the insulating medium. The quantity of energy stored is governed by the character of the medium itself, the electrical stress gradient, and the area of the metal surfaces. The term "dielectric" is usually applied to the insulating medium when its function is to store electrostatic energy, whereas it is usually referred to as "insulation" when its chief purpose is merely to prevent the flow of current.

The ability of a dielectric to store electrostatic energy is expressed as a "dielectric constant." Air and other gases are substantially alike as to dielectric constant. Mediums such as mineral oil are capable of storing two and a half times as much energy as air. A commonly used method of evaluating this property is to express the energy-storage ability in relation to that of air, using the term dielectric constant. If the dielectric constant of a material is 3, it will store three times as much energy as air, other factors being equal.

Dielectric materials are composed of molecules. The behavior of a molecule in an electric field is dependent upon its structure. The molecules of many substances have a symmetric structure. When a symmetric molecule is subjected to an electric field, there is a displacement of the outer layer of electrons with respect to the positively charged nucleus, resulting in what is known as "electronic polarization." This polarization is accompanied by the storage of electrostatic energy and takes place instantly and is instantly reversible in character.

In other substances the molecules are not symmetric. Unsymmetric molecular structures are termed "polar." When a polar material is subjected to an electric field, a second type of polarization occurs. This type of polarization is due to the rotation of permanent molecular dipoles in their attempt to align themselves with the electric field.

There is another type of displacement, known as "atomic polarization," which depends on relative movement of the positively and negatively charged atoms in the molecule. In addition, free ions in the dielectric may migrate in the electric field and accumulate at barriers until the electric field is removed or reversed. This type of polarization, known as "interfacial polarization" or "dielectric absorption," depends on the presence of ions in the material and the structure of the material. The effect is quite noticeable when the duration of the applied field is comparable to the time required for this migration to take place.

The term dielectric constant, which is a measure of these polarizations, has been ill chosen since it is by no means a constant. The electronic and atomic types of polarization are independent of frequency, up to the optical range, and very slightly dependent on temperature. The dipole polarization varies with frequency and fluidity of the substance but is independent of voltage. The interfacial, or dielectric-absorption, effect is greatly influenced by frequency, temperature, viscosity, and voltage stress.

In view of the above, the dielectric constant of many substances has little meaning except when the conditions under which it is determined are defined.

EARLY CAPACITORS

One of the earliest types of capacitors was the Leyden jar. The Leyden jar consists of a glass jar having a coating of metal foil inside and outside extending only part way up from the bottom. The glass body of the jar serves as the dielectric. A means is provided to make electrical connection to the inner and outer coatings. Typical Leyden jars have a capacitance of 0.002 to 0.004 μf. The Leyden jar was first a laboratory curiosity and was later used as a means of storing electrostatic energy in connection with medical devices. Still later the jars were used merely as convenient forms of high-voltage capacitors for lightning protection and radio transmission.

The search for a means of greatly increasing the working area of the dielectric and reducing the thickness well below that of glass eventually led to the use of sheets of mica stacked alternately with metal foils. Mica capacitors played an important role in the early days of radio and are still used extensively in applications where the frequency is high and where very low losses are of prime importance.

The area obtainable with mica, while large compared with Leyden jars, was still inadequate for applications requiring energy storage at relatively low voltages and where relatively low frequencies, such as 60 cycles, were to be used.

The most practical and most economical method of providing very large areas is to use paper suitably dehydrated and impregnated with a dielectric liquid or wax. Paraffin-wax-impregnated paper capacitors were perhaps first used in the telephone industry. Paraffin wax was soon replaced by mediums capable of giving a higher dielectric constant. A typical example of such a material is chlorinated naphthalene.

Wax-impregnated paper capacitors have been used extensively for the past 40 or 50 years in applications requiring relatively small capacitance. Attempts to build them in large sizes were unsuccessful because of the presence of voids and the difficulty of removing heat associated with a-c service, where repetitive charge and discharge is accompanied by continuous energy loss in the dielectric.

Paper capacitors impregnated with a liquid dielectric medium proved to be the solution to the problem of voids and thermal limitations. The first liquid used for this purpose was mineral oil. Mineral-oil-impregnated paper capacitors have been extensively used for the past 30 years. However, during the last 14 years synthetic liquids have been used in most power applications because of the higher dielectric constant, superior performance, and lighter weight of a given rating.

ROLE OF THE DIELECTRIC IN CAPACITORS

Most electrical equipment depends on solid liquid or gaseous insulation in some form to maintain current flow in the desired channels or to prevent short circuits. In equipment other than capacitors the purpose of the insulation is, as the name implies, merely to insulate, or separate, conductors. The insulation must have the required mechanical properties to maintain its continuity and effectiveness. It must be capable of remaining effective under the temperature conditions likely to prevail. It must measure up to certain requirements as an insulator. It is, however, rarely stressed at more than 10 to 100 volts per thousandth of an inch. On 60-cycle voltages the energy stored is negligible, and the heating resulting therefrom is of small consequence. The working temperature of the insulation is governed by heat from other sources, such as I^2R loss in the conductors or iron loss in magnetic circuits.

It is necessary to use liberal quantities of insulation in most apparatus because of methods of manufacture, mechanical requirements, types of material adaptable, and many other practical reasons. Liberal quantities of insulation generally do not penalize the design because it is usually not a large factor in cost or in the dimensions of the finished device.

In a device such as a power capacitor the insulation, or dielectric, as it is more often called, is the actual working element. The size, cost, and weight of the capacitor depend for the most part on the dielectric constant of the dielectric and the voltage applied per unit of thickness.

The importance of this difference may be more appreciated by comparing the amount of dielectric required in a 15-kva capacitor on the basis of conventional insulation practice, present capacitor materials, and voltage per mil stress with the amount required on the basis of usual practice in other electrical equipment.

A 15-kva capacitor for 60-cycle service may use 324 cu in. of paper dielectric impregnated with a chlorinated hydrocarbon compound having a dielectric constant of 4.8 and a voltage stress of 343 volts per mil. If the capacitor dielectric were made from materials such as are used in electrical equipment having a dielectric constant of 2.8 and stressed at 100 volts per mil, the dielectric required in a 15-kva capacitor would have a volume of about 6,500 cu in. instead of 324, and the 15-kva unit would weigh 1,050 lb instead of 52.

This comparison is not intended to imply that the insulation used in motors, transformers, and other such equipment is inferior. Actually, it has been well chosen and improved in many ways over the last 30 years. There is little need to work the insulation harder in this equipment, and there is certainly no advantage in the use of materials of higher dielectric constant, where storage of energy in the insulation is not desired. Furthermore, in most electrical equipment insulation must not only maintain an electrical separation of conductors but often serve as a structural member and withstand mechanical forces. In a cable, for example, insulation must withstand damage by bending. In many ways the conditions in a capacitor are more favorable, and even the same materials can readily be worked harder from the standpoint of voltage stress.

Since the role of insulation in a capacitor is primarily to store electrostatic energy and since the energy stored increases as the square of the voltage stress and directly with dielectric constant, the factors of stress and dielectric constant have been of foremost importance in the development of power capacitors.

EARLY POWER-CAPACITOR DESIGNS

It became obvious some 25 years ago that the most practical construction for power capacitors consisted of using a large area of metal foil separated by paper layers and impregnated with and submerged in a liquid having good electrical qualities. The first successful power capacitors contained linen paper and tin foil and were impregnated with mineral oil.

Over the first 12 or 14 years, many improvements were made in materials and methods of fabrication. Stacking of layers of paper and foil soon gave way to winding. Wood-pulp paper was greatly improved as to purity and methods of fabrication and it finally replaced linen, owing to its greater freedom from conducting materials, lower cost, and superior performance in many respects.

There were at first two schools of thought with respect to the design of the capacitor assembly. One school advocated winding many small capacitor elements, assembling them in groups, impregnating and testing them, and finally assembling them into large tanks, similar to transformers, with kva ratings up to several hundred kva. The other school advocated construction of small capacitor units, completely assembled before processing, and using a multiplicity of these units to make up a bank of capacitors.

The large-tank type has many disadvantages, which may be enumerated as follows:

1. Elements must be handled after impregnation and are subject to exposure or damage.
2. Manufacturing operations are undesirable because of the necessity of keeping the windings under liquid during testing and assembly operations.
3. Individual groups or windings must be fused in the final assembly; rupture of fuses may damage the entire assembly.
4. Costs are high because of nature of construction, and field failures are more serious because of loss of large assemblies.
5. Lower stresses must be used because of the greater probability of faults in completed units due to the size of a single assembly.

There are many advantages to be found in the unit type of construction, some of which are as follows:

1. Designs lend themselves to quantity production.
2. Higher stresses may be used because of the ease with which the weak units can be weeded out on production tests, and the dependability of large installations is greater since failures will be limited to replaceable parts of the whole bank. Individual fuses are more practical and can be designed with sufficient rupturing capacity to remove a faulty unit without affecting the remainder of the bank.

From the standpoint of design and manufacture, the individual capacitor units should be as small as physically possible. There are, however, limits on the size. First, the units should not be so small in size as to prohibit adequate space for terminal bushings for the various voltages to be encountered; and second, they should not be so small that the cost per kva is unnecessarily increased by the cost of case, processing, and terminals. Many costs are relatively fixed, such as terminal bushings, case, processing, and assembly labor, and these will be the same regardless of kva rating. If the unit is reduced in size below a certain range, the increase in cost per kva due to these factors becomes very important.

If the individual capacitor unit is made excessively large, the mathematics of probability and experience show that the dielectric must be made more liberal; otherwise the number weeded out on test and in the first few years of service would be increased beyond reasonable limits.

The above factors were weighed very carefully in the early days of development and it became apparent that a satisfactory size of unit from a manufacturing standpoint was one having base dimensions of 4 to 5 in. in width, 13½ in. in length, and a height of 12 to 14 in. Such a unit was easy to handle and install in racks in the field. The unit was sufficiently small to permit relatively high stresses, and the weeding out on tests of completed units containing flaws did not result in an unreasonable loss of material and labor.

The first quantity-production capacitors of this type were rated at 5 kva and 1,328 volts. These were Y-connected to 2,300-volt systems. If the system voltage was lower or higher, transformers were used to adapt the capacitor to the circuit. The Y connection permitted designing the individual dielectric to stand 1,328 volts, which presented fewer problems than designing for 2,300 volts. It was found undesirable to design single layers or dielectrics for 2,300 volts because of the damaging effect of corona during the over-potential tests.

The need for capacitors for 230-, 460-, and 575-volt circuits was recognized from the beginning, but the cost of such capacitors was generally higher per kva than the cost of a transformer in combination with 1,328-volt capacitors for the following reasons:

1. If the kva of a given size of capacitor unit for lower voltages is to be maintained, the voltage per mil must be kept constant.
2. On 460 volts, the insulation thickness must be reduced to less than ⅓ of that used for 1,328 volts and for the sake of diversity there must not be less than three layers. The area of this thinner

dielectric must be about three times as great because the total weight of dielectric must be the same, if the kva rating is to be the same.

3. On 230 volts, the insulation thickness must be reduced to about 1/6 of that used for 1,328 volts if the quantity of insulation is to remain constant.
4. If the thickness is reduced in proportion to voltage and the area increased in like manner, the kva will remain the same. The cost of this paper is considerably greater, however, because it is very thin.
5. The cost of foil will be increased by a factor of 3 or 6, because of the increase in area necessary.
6. The cost of winding will be increased by a factor of 3 or 6, since the winding labor varies substantially with area.

It will be seen from the above that the 460- or 230-volt capacitors tend to cost a great deal more than 1,328-volt capacitors even if the dielectric insulation is reduced directly with voltage.

In the early days of capacitors, it was found impossible to build 460-volt capacitors with the same volts per mil stress as 1,328-volt capacitors. In actual designs, the dielectric insulation was reduced much less, so that the volts per mil for a 460-volt capacitor was considerably less than the volts per mil for a 1,328-volt unit. The condition was even more accentuated for a 230-volt capacitor. The limitations on paper thickness, combined with large area and prevalence of conducting particles in the paper and other types of flaws, made it necessary to work at considerably lower voltage stress with 230-volt capacitors than with 460-volt capacitors. In some early designs, the 230-volt unit was rated at 2 kva and occupied about the same space as a 1,328-volt 5-kva unit and cost even more per unit. This resulted in a cost per kva of more than double.

With these design handicaps, it was found that the first cost of either 230- or 460-volt capacitors was higher than a combination of a transformer and a 1,328-volt capacitor. Consequently, in the application of power capacitors on 230- or 460-volt circuits, it became common practice first to raise the voltage to 1,328 volt with a transformer and then apply a 1,328-volt capacitor. The kva rating of the transformer and the capacitor must be substantially the same.

Since transformer losses are considerably higher than capacitor losses, the total losses in such a combination were considerably higher than the losses of a capacitor designed for these low voltages. In some cases, where the losses were quite important owing to the charge for energy, these high-cost 230-volt capacitors were used even though the first cost of the installation was higher. The 460-volt capacitors were more often used since their first cost was lower than 230-volt capacitors. Direct-connected 460-volt capacitors, however, were still the exception rather than the rule.

Improvements soon resulted in 460-volt direct-connected capacitors with costs sufficiently low to eliminate entirely the practice of using transformers on 460-volt circuits.

The use of series-connected sections inside the capacitor unit made it possible to build capacitors for 2,300 volts and above.

Over a period of time, the paper was constantly improved, resulting in great uniformity, higher purity, and fewer conducting particles. Aluminum foil was substituted for tin foil. Being stronger, and higher in thermal conductivity, it was used in thinner gauges without difficulty in winding and its conductivity improved the heat transfer from the dielectric to the case surface.

Improvements in mineral oil and processing combined with improvements in paper and manufacturing technique made it possible to increase the kva rating of the 2,400-volt units from 5 to 10 with very little change in the physical size. The same type of improvement was reflected in the ratings for higher voltages.

These substantial gains were not possible for 230-, 460-, and 575-volt units, but some considerable increases were made in kva ratings, particularly for 460- and 575-volt units, for the same physical size and cost. The use of transformer-connected capacitors was discontinued except for 230-volt ratings and installations on circuits above 4,800 volts.

Today capacitor units are designed for all standard voltages from 230 to 13,800. The use of transformers is limited to applications on circuit voltages below 230 volts. Capacitors for 230-volt application, however, are still more costly per kva than 460- or 2,400-volt capacitors by a factor of about 2, but where 230-volt circuits are used, the advantage of directly connecting 230-volt capacitors is often great enough to favor their use rather than apply the power-factor corrections on the high-voltage side of the service transformer. The cost of 230-volt capacitors has been reduced to a point where it generally does not pay to use a transformer in combination with higher voltage capacitors.

Where the plant circuits are long and voltage drop is an important factor, placing the capacitors out on the 230-volt feeder results in enough additional gains to justify the 230-volt capacitors even at twice the first cost per kva over capacitors on the high-voltage circuit to the plant.

To use transformers in combination with lower cost high-voltage capacitors introduces considerable additional loss and requires much space, and often special enclosures.

SYNTHETIC IMPREGNANTS

Even from the early days of power capacitors there was a strong desire to make use of liquid impregnants which would give a resulting dielectric constant higher than that obtainable with mineral oil. This would provide a direct means of increasing the kva per pound of dielectric at the same volts per mil stress, and it would to a large extent solve the material limitations associated with 230- and 460-volt capacitors.

Castor oil offered considerable advantages from the standpoint of dielectric constant, since it is a polar material capable of being polarized by molecular orientation. It was found, however, that capacitors impregnated with castor oil were not stable, and while these capacitors performed quite satisfactorily on direct current, they were not reliable on continuous a-c service.

Chlorinated naphthalene, a waxlike solid, also had a high dielectric constant but large capacitors could not be made with a wax impregnant because of voids and thermal difficulties; nor were capacitors of this type stable on 60-cycle continuous service except at stresses which made them uneconomical compared with mineral oil.

The use of chlorinated aromatic hydrocarbon compounds started some 14 years ago. These are still the most satisfactory of all liquid impregnants for 60-cycle power capacitors because of their high dielectric constant, superior performance, lack of affinity for water, and the fact that the fire hazard associated with an insulation failure is eliminated.

The use of a liquid of high dielectric constant plus further improvements in paper and manufacturing control made it possible to produce a 7½-kva 230-volt capacitor, and a capacitor rated at 15 kva in substantially the same physical size for all higher voltages up to 13,800 volts, even including the difficult 460- and 575-volt ratings. All these ratings are still in the physical size class which retains the desirable manufacturing advantages.

CAPACITOR LOSSES

In the early designs using mineral oil and employing working stresses of 200 or 275 volts per mil, the losses were not important except in so far as they reflected the quality of the processing. The temperature rise of these units was so low as to be of little consequence. The kva per unit of case surface was low and the loss could be 0.5 per cent or even more without resulting in substantial rise in case surface temperature or capacitor internal temperature.

With an increase in stress up to 340 to 350 volts per mil and the increase in the dielectric constant made possible by the use of synthetic impregnants, the kva per pound of dielectric was increased, and the larger kva rating in the same container resulted in the need for radiating considerably more heat loss from each square inch of case surface. This resulted in a substantially greater rise in temperature even with a reduction in power factor to less than ⅓ per cent. These relations are shown in Table 1.

TABLE 1. CAPACITOR VOLTAGE STRESS AND THERMAL LOADING OF CASE SURFACE

Stress, volts per mil	Dielectric, cu in. per kva	Loss per cu in. of dielectric, watts	Loss per kva, watts	Loss per sq in. of case area, watts
200	129	0.04	5.16	0.035
275	68	0.06	3.88	0.052
343	24	0.135	3.25	0.084

The approximate case temperature rise in degrees centigrade for the first rating in Table 1 is 6°C, the second 8.6°C, and the third 14°C.

The purpose of Table 1 is primarily to show that a similar gain cannot be made by the use of a liquid with still higher dielectric constant because designs have now reached the point where temperature has become a factor of importance. A material of higher dielectric constant would have merit only if it made possible lower losses at the same time.

Since loss limits are not yet encountered in 230-volt design owing to present material limitations necessitating substantially reduced stresses, a material of higher dielectric constant would be desirable in this range of ratings even though the losses in per cent of kva were not reduced.

CHARACTERISTICS OF CAPACITORS

A complete or even general discussion of the characteristics of the most common materials or even the impregnants which have been used with paper would involve too much space in a work which is primarily intended to deal with a-c power capacitors. For this reason the discussion will be limited to power capacitors which have been manufactured in commercial quantities. Since only two types of impregnants have been so used, viz., mineral oil and chlorinated diphenyl, the characteristics of these will be discussed.

As pointed out, the first successful power capacitors contained paper dielectric impregnated with mineral oil. Mineral oil made possible large capacitors, compared with the relatively small telephone type or radio capacitors.

Mineral oils have been used in electrical apparatus since the early days of the electrical industry. When properly refined and purified, their conductivity is very low and the breakdown strength is high. Mineral oils have certain limitations, however, as follows:

1. Their dielectric constant is relatively low.
2. Voltage distribution through the dielectric is not uniform.
3. They are subject to oxidation and the oxidation products are acids, water, and solid polymerization products called sludge.
4. They are attacked by gaseous electrical discharge, producing hydrogen and low-molecular-weight hydrocarbons and a solid polymerization product often referred to as "X-wax."
5. They are inflammable and this results in greater installation expense to provide for safety.

The low dielectric constant results in larger capacitors. This can only be offset by working the dielectric at a high voltage per unit of thickness. Experience has shown that stresses must actually be kept on the conservative side because of other inherent limitations.

The dissimilarity of dielectric constant of paper and oil also makes it necessary to keep the voltage stress on the conservative side and to assemble the capacitor firmly to reduce the oil films to a minimum. This need for relatively high assembling pressure is unfortunate for experience also shows the need for light pressure and relatively liberal oil films to minimize the effect of conducting particles in the paper, particularly in the case of low-voltage capacitors containing thin insulation.

In capacitors oxidation and sludge formation are not a serious problem because of the relatively low working temperatures. However, some care must be exercised in the selection of stable oils for other reasons.

The design of oil capacitors must be such that the voltage impressed on single dielectric layers will be well below the level where ionization or corona exists. Consideration must be given not only to the working voltage but to the voltage which may be applied during overpotential tests. Ionization produced in voids as a result of tests may leave permanent gas pockets in which further ionization will take place even at working voltage. Once such ionization is initiated, solid waxy by-products, commonly called "X-wax," will form and the life of the dielectric at points of ionization is definitely limited.

It is equally important to avoid the use of an oil which solidifies at low temperatures such as may be encountered in service. Voids so produced permit ionization which results in hydrogen bubbles. Once these hydrogen bubbles are established ionization can and does continue and failure may occur at normal working temperatures as a result of subsequent deterioration.

In view of these limitations it has generally been desirable to give very careful consideration to working stresses, dielectric-layer voltages, and application of voltage to oil capacitors while at very low temperatures.

One decided advantage possessed by mineral-oil capacitors is the small change in capacitance over a wide range of temperature. While this does not result in any advantage in power-factor improvement on lines and in industrial plants, it is of considerable importance in certain special applications where change in capacitance alters the performance of the system. One excellent example is a capacitor motor used in outdoor service. The starting torque of the motor would be seriously affected by a substantial departure of the capacitance from the value assumed by the motor designer. Another example is a monocyclic square constant-current regulator whose performance as a regulator depends on resonant circuits. Even though mineral oil is used very little in power capacitors today, it is still desirable in many special applications involving low temperature where relatively constant capacitance is required.

These limitations of mineral oils have stimulated a considerable amount of research for the improvement of oil performance with respect to its ability to withstand ionization and oxidation.

It has been found that, in general, oils containing a high proportion of aromatics produce less gas on ionization. Highly saturated oil, rich in paraffin hydrocarbons, shows the highest rate of gas evolution. Considerable improvements have been made by the addition of inhibitors.

Even though the capacitance of mineral oil is substantially constant at 60 cycles it is by no means constant at the higher frequencies. Figure 1 shows the variation of capacitance observed using frequencies from 60 cycles to 1 megacycle.

The a-c properties of impregnated-paper capacitors are determined by both the paper and the impregnant. If, however, the impregnant is a polar material such as chlorinated diphenyl, the over-all characteristics are determined to a large extent by the special properties of the impregnant. Polar liquids depend on the rotation of molecules for part of the dielectric constant, and under certain conditions only part of the rated capacitance may be effective. Below certain temperatures a part of the dielectric constant contributed by molecular rotation may be lost through decreased response of the molecular dipoles to the applied field. If the frequency is raised, the temperature below which no dipole rotation occurs is higher. If the frequency is maintained and the viscosity is reduced by addition of more fluid dipolar materials, the rotation takes place at a lower temperature.

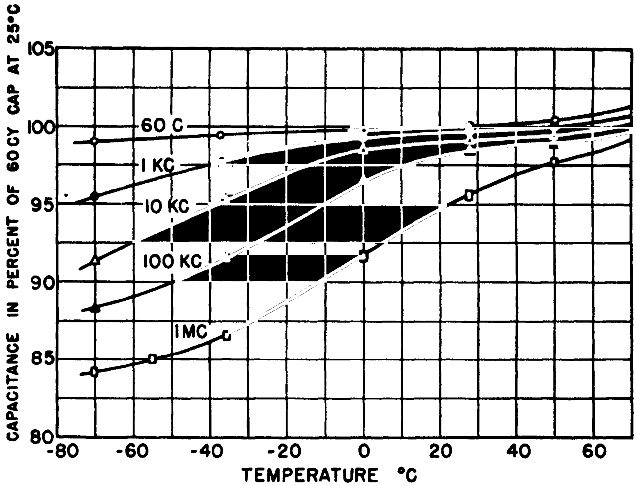


FIG. 1. Capacitance–temperature behavior at various frequencies of capacitor impregnated with mineral oil.

Dipolar rotation takes place more readily as the freezing point of the liquid is reduced. It occurs less readily if the speed of rotation is increased as is the case when the frequency is raised.

Figure 2 shows the changes in capacitance with changes in capacitor temperature, using test frequencies of 60 cycles to 1 megacycle, and a chlorinated diphenyl averaging five chlorine atoms per molecule.

Compositions consisting of pentachlorodiphenyl and chloroethylbenzene have been made for the purpose of shifting these curves to the left and causing the dipole rotation to take place at lower temperatures. Figure 3 shows the change in capacitance with such compositions.

The losses in mineral oil capacitors are quite low, particularly when a high quality of oil is used. Figure 4 gives typical values of dissipation factor for mineral-oil-impregnated capacitors.

The losses in paper capacitors impregnated with pentachlorodiphenyl are affected by the viscosity of the impregnant, which in turn is governed by the temperature. At the temperature region where polar rotation takes place with great difficulty, the losses reach a maximum. At still lower temperatures rotation is restricted until finally no appreciable rotation occurs and the losses are again low. Figure 5 shows the

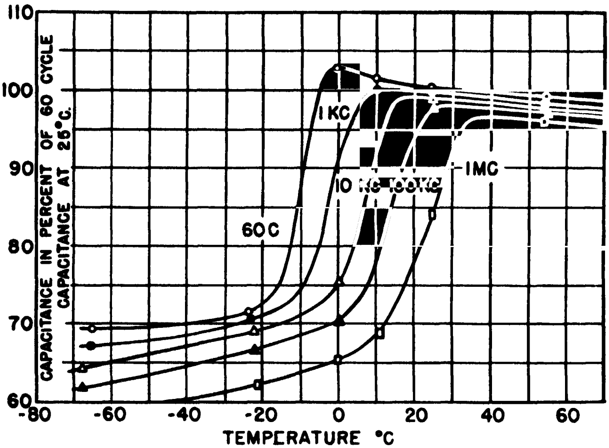


FIG. 2. Capacitance–temperature behavior at various frequencies of capacitor impregnated with Inerteen (pentachlorodiphenyl).

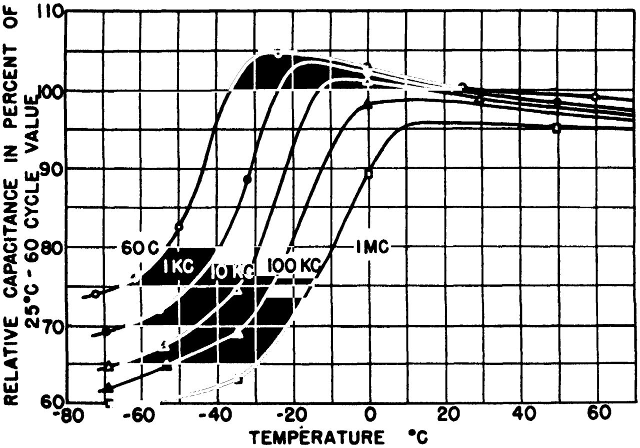


FIG. 3. Capacitance–temperature behavior at various frequencies of capacitor impregnated with modified Inerteen (pentachlorodiphenyl plus polychloroethyl benzene).

dissipation factor for paper capacitors impregnated with pentachlorodiphenyl.

Pentachlorodiphenyl compounds have found extensive use as impregnants not only for power capacitors but for capacitors for radio and

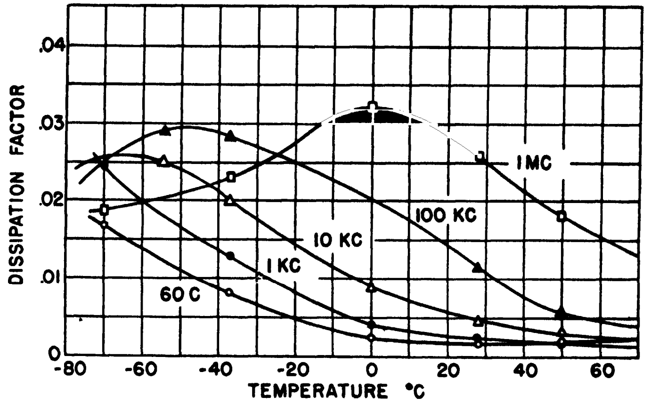


FIG. 4. Dissipation factor–temperature behavior at various frequencies of paper capacitor impregnated with mineral oil.

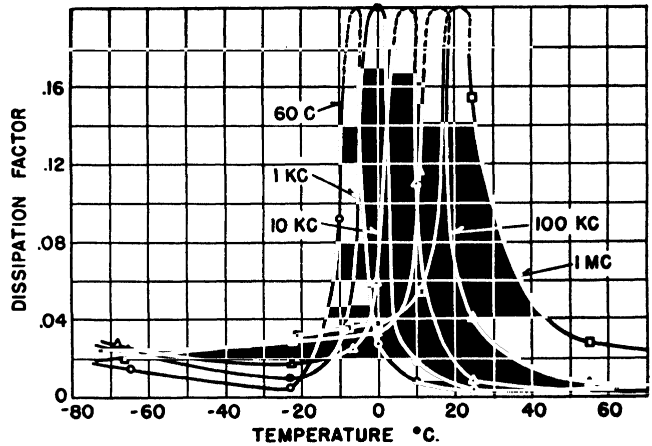


FIG. 5. Dissipation factor–temperature behavior at various frequencies of paper capacitor impregnated with Inerteen (pentachlorodiphenyl).

general electronics applications. They have been successfully used over the past 8 years on high-frequency power applications such as inductive heating up to 10,000 cycles and for capacitors used in fluorescent-lamp ballasts. This type of material has largely replaced mineral oil and similar materials as a capacitor impregnant due to its high dielectric constant, excellent oxidation stability, noninflammability, and other desirable properties. These materials have been the subject of a number of investigations and the results are reported in literature.

While several types of chlorinated hydrocarbons have been used, the type which has come into most extensive use in capacitors is a chlorinated diphenyl averaging about five chlorine atoms per molecule. Some of the physical and electrical characteristics of this liquid are given in Table 2.

TABLE 2. SOME PHYSICAL AND ELECTRICAL PROPERTIES OF CHLORINATED CAPACITOR IMPREGNANT

Density, 25°C	1.54
Refractory index, 25°C	1.638
Pour point, A.S.T.M.	+10°C
Flash point (open cup)	None
Fire point (open cup)	None
Viscosity—Saybolt seconds	2,800 at 100°F
Viscosity—Saybolt seconds	46 at 210°F
Dissipation factor,* 25°C	0.1
Dissipation factor, 85°C	0.1
Dielectric constant, 25°C	5.
Dielectric constant, 85°C	4.5

* Dissipation factor is defined as the tangent of the loss angle, whereas power factor is the sine of the loss angle. For values of either less than 0.1, they are equal for all practical purposes.

To sum up the characteristics of mineral oil and pentachlorodiphenyl, the latter makes it possible to design smaller capacitors because of the higher dielectric constant, and because it is possible to operate at somewhat higher voltage stresses without fear of ionization and formation of waxy by-products within the dielectric. The striking difference is shown in Fig. 6, comparing a 10-kva mineral-oil capacitor and a 10-kva Inerteen (pentachlorodiphenyl) capacitor designed for comparable performance.

While the capacitance of an Inerteen (pentachlorodiphenyl-impregnated) capacitor may vary with capacitor temperature, as shown in Fig. 2, it should be noted that such variation will not take place when the capacitor is continuously energized on 60 cycles and at a voltage of 50 per cent or more of the rated voltage. Even when the applied voltage is only 25 per cent of rating, the capacitance will not drop below rated value unless the air temperature is well below 0°C.

Table 3 shows a test on a 460-volt 15-kva 60-cycle capacitor unit operated at 25 per cent of rated voltage in an oven where the air temperature is slowly reduced.

The tests in Table 3 were repeated except that the applied voltage was 50 per cent of rated voltage. These values are shown in Table 4.

TABLE 3. CAPACITANCE AT LOW TEMPERATURES AND 25 PER CENT OF RATED VOLTAGE

Time, hr	Air temperature, °C	Voltage on capacitor	Capacitance, per cent of capacitance at 25°C
0	−27	115	99 5
1	−32	115	100 5
2	−53 5	115	96 3
3	−58	115	74 8
4	−60	115	73 5
5	−60	115	73
6	−60	115	73
7	−60	115	73
8	−60	115	73

If a capacitor of this type is allowed to remain at a low temperature until the capacitance drops to the minimum value of 73 per cent of the 25°C capacitance and is then energized at rated voltage, the dielectric losses will warm up the dielectric and the dipole rotation will take place at an increasing rate, until finally the capacitor kva is normal and will remain so as long as the capacitor is energized. The time required for this warm-up operation depends on the temperature of the capacitor when energized. Obviously, if the capacitor is at a uniform temperature

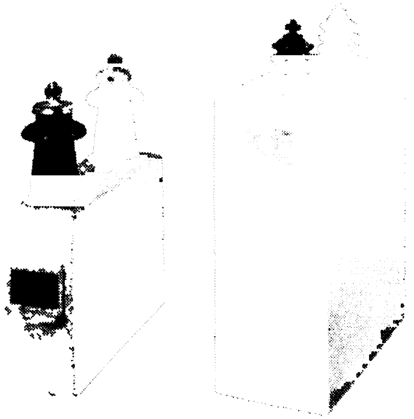


FIG. 6. Comparison in size of a 10-kva, 2,400-volt, 60-cycle mineral-oil capacitor with a small Inerteen capacitor of the same rating.

of −50 or −60°C, considerable time will be required. However, if the capacitor is only a few degrees below zero the time will be measured in minutes.

Table 4. Capacitance at Low Temperatures and 50 Per Cent of Rated Voltage

Time, hr	Air temperature, °C	Voltage on capacitor	Capacitance, per cent of capacitance at 25°C
0	−40	230	102
3	−59.8	230	101.5
6	−61	230	100
9	−61	230	101
11	−61	230	101

Figure 7 shows energizing tests started at temperatures down to −16°C and Fig. 8 gives similar information in more useful form.

Capacitors of this type when energized at low temperature will have low losses after coming up to normal capacitance and will not operate in a region where the losses are high. During the warm-up period, the losses will, however, be high because of restricted polar rotation. Figure 9 shows a trace of losses from moment of energization until equilibrium, for starting temperatures down to −12°C. Where the starting temperature is lower the time required is longer, but the losses will be quite low

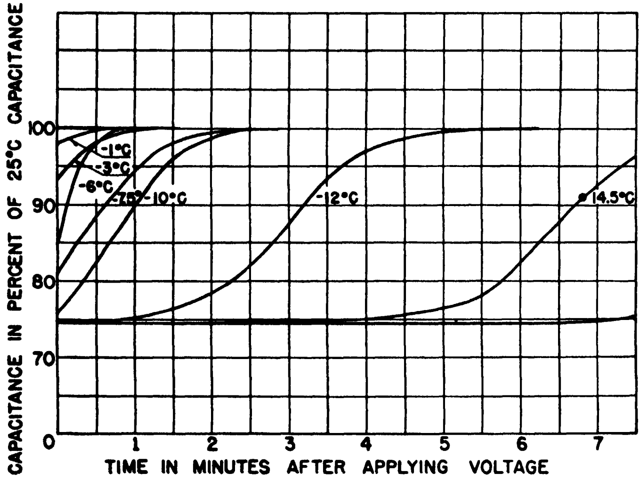


Fig. 7. Capacitance–time curves for Inerteen capacitors, capacitor energized at rated voltage while at the capacitor temperature indicated.

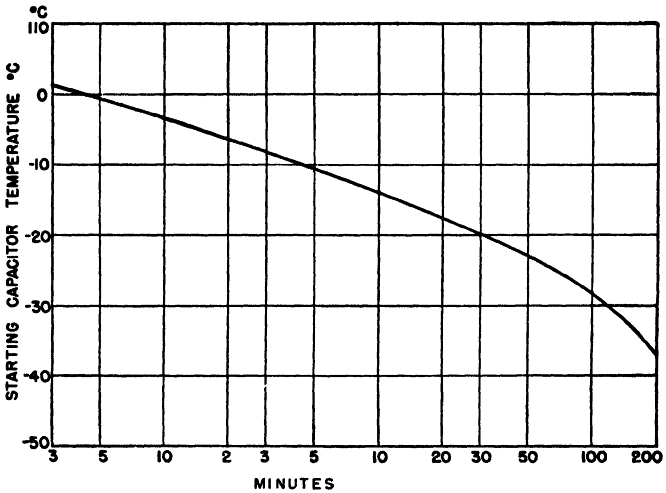


Fig 8 Capacitor kva time curve, showing time required for capacitor to warm-up and reach rated kva when energized at rated voltage while at the capacitor temperature indicated

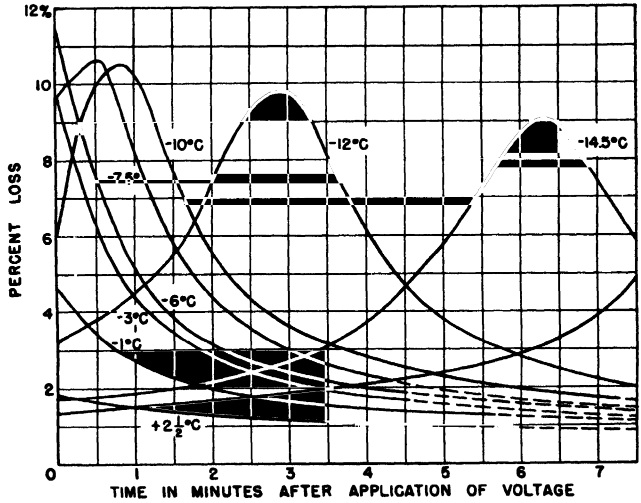


Fig. 9. Loss–time curves, capacitor energized at rated voltage while at the capacitor temperature indicated, showing time required for the losses to approach the final low steady value.

at the final equilibrium temperature. The ultimate loss of one-third of 1 per cent cannot be shown on the scale used.

Bibliography

BERBERICH, L. J.: Influence of Gaseous Electric Discharge on Hydrocarbon Oils, *Ind. & Eng. Chem.*, vol. 30, p. 280, March, 1938.

BERBERICH, L. J., C. V. FIELDS, and R. E. MARBURY: Characteristics of Chlorinated Impregnants in D.C. Paper Capacitors, A.I.E.E. Summer Meeting, St. Louis, June 26–30, 1944.

BROTHERTON, M.: Paper Capacitor Under Direct Voltages, *Proc.* I.R.E., vol. 32, pp. 139–143, 1943.

CLARK, F. M.: Noninflammable Dielectric Organic Compounds, *Ind. Eng. Chem.*, vol. 29, pp. 698–702, 1937.

GARTON, C. G.: Dielectric Loss in Thin Film of Insulating Liquids, *J.I.E.E.* (London), vol. 88 III, pp. 23–40, 1941.

JACKSON, W.: Dielectric Loss Characteristics of a Chlorinated Diphenyl, *Proc. Roy. Soc.* (London), vol. 153*A*, pp. 158–166, 1935.

McLEAN, D. A., L. EGERTON, G. T. KOHMAN, and M. BROTHERTON: Paper Dielectric Containing Chlorinated Impregnants, *Ind. Eng. Chem.*, vol. 34, pp. 101–109, 1942.

MARBURY, R. E.: Recent Advance in the Manufacture and Testing of Static Condensers in Power Sizes, A.I.E.E. Midwinter Convention, Philadelphia, Feb. 4–8, 1924.

MARBURY, R. E., and A. L. ATHERTON: Dielectric Stresses in Static Capacitors for Power Factor Correction, *Elec. J.*, pp. 332–337, Sept., 1923.

MORGAN, S. O.: Two Types of Dielectric Polarization, *Trans. Electrochem. Soc.*, vol. 65, pp. 109–118, 1934.

RACE, H. H., R. J. HEMPHILL, and H. S. ENDICOTT: Important Properties of Electrical Insulating Papers, *Gen. Elec. Rev.*, vol. 43, pp. 491–499, 1940.

STOOPS, W. N.: The Dielectric Properties of Cellulose, *J. Amer. Chem. Soc.*, vol. 56, pp. 1480–1483, 1934.

WHITE, A. H., and S. O. MORGAN: The Dielectric Properties of Chlorinated Diphenyls, *J. Franklin Inst.*, vol. 216, pp. 635–644, 1933.

WHITEHEAD, J. B.: "Impregnated Paper Insulation," John Wiley & Sons, Inc., 1935.

WHITEHEAD, J. B.: "Lectures on Dielectric Theory and Insulation," McGraw-Hill Book Company, Inc., 1937.

CHAPTER 2

CAPACITOR RATING, DESIGN, AND MANUFACTURE

METHOD OF RATING POWER-CAPACITOR UNITS

Capacitance. Prior to their use on power circuits, capacitors were always rated in microfarads. A microfarad is a millionth part of a farad. This unit was convenient to use since most applications were on communication equipment where calculations were in terms of microfarads.

When capacitors are used to improve power factor, the item of primary concern is the magnetizing current of power loads such as induction motors. The product of the magnetizing current and the line voltage determines the reactive component of the load, and this is usually expressed in lagging volt-amperes. Since the resulting power factor is determined by the extent that the lagging volt-amperes are supplied by capacitors, it is convenient to rate the capacitor in volt-amperes and since the capacitor volt-amperes are reactive, the expression var is used. To avoid large numbers the factor of 1,000 is used, giving the basis of rating, kvar.

A capacitor rated at 1 kvar will draw 1,000 va of reactive current. The relation to the microfarad unit is easily expressed as

$$\text{Kvar} = \frac{E^2\, 2\,\pi fC \times 10^{-6}}{1{,}000}$$

where E = rms voltage.
C = capacitance, μf.
f = frequency, cycles.

The current that a capacitor will draw from the circuit is directly proportional to voltage, capacitance, and frequency.

$$I = E\, 2\pi fC \times 10^{-6}$$

The capacitive reactance of a capacitor is inversely proportional to frequency.

$$X_C = \frac{1 \times 10^6}{2\pi fC} = \text{ohms}$$

In designing a capacitor to have a given kvar rating it is necessary to convert kvar to capacitance in farads or microfarads, for the particular voltage and frequency with which we are concerned. For a given kvar rating the capacitance in microfarads varies inversely as the square of the voltage and directly with frequency in cycles.

In designing a capacitor for a determined capacitance in microfarads it is necessary to take into account the fact that all variables are not controllable, such as the thickness of the dielectric material, winding tension, and assembly pressure. Slight variations in the paper thickness, variations in clamping pressure, and other variables cause variations in the capacitance of the finished capacitor. In a given lot of capacitors this variation is about 3 or 4 per cent from a mean value, but from lot to lot the mean value may shift much more. It is customary to allow a variation of ±7.5 per cent in capacitance to take care of these manufacturing variations.

In determining the required capacitance in microfarads corresponding to a particular capacitor rating in kvar, a factor of +7.5 per cent is added, and a permissible manufacturing limit of 0 + 15 per cent is used. In this manner the capacitor rating in kvar will be surely realized and all manufacturing variations will be in the direction to give equal or more than rated kvar.

When applying capacitors on a kvar basis one is sure to obtain a minimum kvar equal to the capacitor rating so long as the voltage is equal or more than the capacitor voltage rating.

The size of a capacitor in kvar is governed by many factors such as

1. Application.
2. Voltage.
3. Phases.
4. Economics.

Obviously some applications may require only a small kvar rating such as ½, 1, or even less. It is necessary, of course, to build ratings for such purposes even though they may cost more to manufacture per kvar than larger capacitors. The improvement of power factor of small loads requiring very small capacitors is sometimes justified by practical considerations. Generally power-factor improvement is made on a sounder basis, such as applying capacitors to a circuit, an entire plant, or an extensive portion of a utility system.

Since most applications require a total kvar of 100 or more, the maximum kvar of a single capacitor unit becomes of great importance. Obviously the unit should be large enough to provide adequate room for terminal bushings. Because of the space needed for terminal bushings it is not desirable or practical to build 1-, 2-, or 5-kvar capacitors for 2,400 volts or higher.

The number of phases also has an influence on the size of capacitor units. For low voltages, such as 230 or 575, it is practical to provide the capacitor with three or four terminals for two-phase or three-phase applications, but for higher voltages it is preferable to build single-phase units and connect three units for three-phase and two for two-phase applications.

TABLE 5. CAPACITOR-UNIT RATINGS IN KVAR

	Ratings for 60-cycle voltage range			
	230 volts, single- and three-phase	460 to 575 volts, single- and three-phase	2,400 to 4,160 volts, single- and three-phase	4,800 to 13,800 volts, single-phase
Special-purpose ratings	0.5	1		
	1.0	2		
	2.5	5		
	5.0	10	10	
General-purpose ratings.	7.5	15	15	15

NOTE: 4,800- and 7,200-volt three-phase units are sometimes used on single-unit outdoor applications but are not convenient to assemble in multiple housings.

As the capacitor unit is made larger and larger the cost per kvar goes down as far as case, terminals, processing, etc., are concerned, but since the probability of defects increases with size, larger units must have more insulation for the same voltage. For this reason, if materials are the same, there is a most economical size from the standpoint of cost per kvar. A 60-kvar capacitor unit may actually cost more than four 15-kvar units. It is preferable, therefore, to assemble a plurality of units to make up large capacitors rather than build large single-capacitor units.

Because of the economic factors stated above much attention has been given to this problem by the industry and standards have been established for capacitor units. The rating of 15 kvar has been chosen because it is a convenient rating with which to obtain the multiplicity of large capacitor bank ratings and because it is in the range where minimum costs per kvar are possible with present materials and processes. As materials improve units of 25 or 30 kvar will be equally desirable.

Table 5 gives the generally preferred unit ratings in kvar of capacitors which are intended primarily for power-circuit application.

Since capacitor units consist of a plurality of internal elements, usually referred to as sections, and since this number can be varied over a considerable range, it is possible to use a number divisible by 3 and arrange the sections in three groups, either delta- or star-connected, and bring out leads through three terminals. Three-phase capacitor units generally are delta-connected internally. Figure 10 shows the internal connections of a three-phase delta-connected capacitor unit. Figure 11 shows the internal arrangement of a two-phase unit, which is simply an arrangement of two internal groups of sections with leads brought out through four terminals.

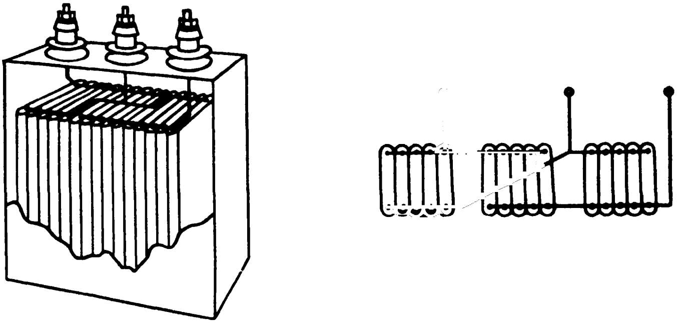


FIG. 10. Fifteen-kva indoor three-phase capacitor—diagram of connections.

Continuous Working Voltage. The continuous working voltage of a capacitor has been defined in industry standards as the average voltage over any 24-hr period. The temperature rise of the capacitor does not become constant until approximately 12 hr have elapsed; thus the average over a 24-hr period has a very close relation to the rise to be expected.

Standard capacitors are intended for use on circuits whose average voltage over any 24-hr period does not exceed the name-plate rating of the capacitor by more than 5 per cent. During the 24-hr period, however, the voltage may reach 110 per cent so long as the average limit of 105 per cent is not exceeded.

The subject of standard preferred voltages has received a great deal of attention because of the many advantages that would result from more uniform practices. The voltage problem with capacitors is somewhat more important than in the case of other apparatus. This is because a capacitor makes its own load. It is simply connected to the circuit, after which it draws a certain kvar. The kvar rating must be on the basis of a certain voltage. If it is used on a lower voltage the effectiveness in terms of kva drops as the square of the voltage. A transformer intended for use on 2,200 volts might be insulated for 2,700 volts with very little effect on cost as long as the rated kva is unchanged. A capacitor unit designed for 2,700 volts, 15 kvar, and used on 2,200 volts will deliver only 11.8 kvar. The total number of capacitor units required for a given kvar on 2,200 volts will be 27 per cent more than if capacitors were used which were actually designed for 2,200 volts. The installation of 2,700-volt rated capacitors can therefore be justified only if future changes in conditions demand 2,700-volt capacitors.

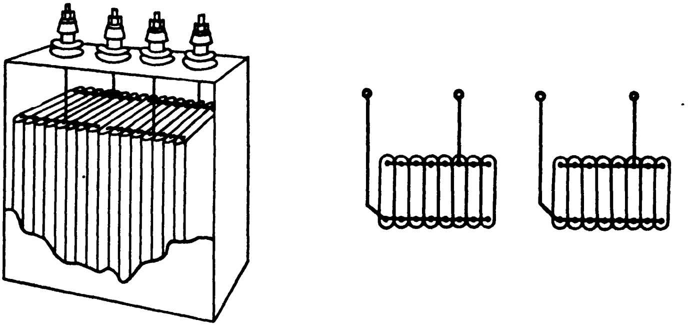


FIG. 11. Fifteen-kva indoor two-phase capacitor—diagram of connections.

It is obvious from the above that it is important to use capacitors at or near their rating for minimum cost per kvar.

TABLE 6. PREFERRED VOLTAGES OF CAPACITOR UNITS

230	4,800
460	7,200
575	7,960
2,400	12,470
4,160	13,800

In the early days of power-factor improvement capacitors were rated at 220, 440, 550, 2,200 volts, etc., and designed to give rated kvar on this basis. Where higher voltages were known to exist special higher voltage units were installed. The higher voltage units could not be made standard until the number of 220-, 440-, and 2,200-volt circuits were in the minority. When this situation was evident the standard voltages were changed to 230, 460, 2,300 volts, etc., and the 220-, 440-, and 2,200-volt ratings became special. The prevalence of 2,400-volt distribution circuits has since resulted in a standard of 2,400 volts, leaving both 2,200- and 2,300-volt ratings nonstandard.

Table 6 gives the present preferred standard voltages for which capacitors units are designed.

Frequency. When standard power capacitors are to be used on frequencies below 60 cycles the kvar will be reduced directly with frequency. Thus if a 75-kvar 25-cycle capacitor is needed, a 180-kvar 60-cycle capacitor must be used. The temperature rise will be lower owing to the lower operating kvar, and ambient-temperature limits stated for 60-cycle use do not apply for 25-cycle use.

Where a plurality of 60-cycle capacitor units are assembled together in combination with a circuit breaker or switch chosen on the basis of the 25-cycle application, taking into account the reduced working current, the entire assembly is usually rated on the basis of 25 cycles and so indicated on the name plate covering the complete assembly. The capacitor units, however, are usually rated in terms of the maximum permissible working frequency.

Capacitor units may be designed for frequencies above 60 cycles and, if cooled by natural air circulation, are usually rated for the same kvar when the dimensions are the same. This is not the case, however, for the 230-volt capacitors where the case surface is liberal and capable of radiating more losses than represented by the 60-cycle rating. Where artificial cooling means are employed the kvar rating for the same size unit may be substantially increased where high-frequency ratings are assigned to the units.

Wave Form. In the design of capacitors for application to power circuits it is recognized that wave forms are not perfect sine waves, and that the operating kvar of the capacitor will be higher than intended by an amount equal to the effect of harmonics present in the voltage wave. In considering the ambient temperature, permissible working voltage, and case surface available for radiation of losses, it is necessary to place some limit on the amount of departure from a true sine wave that can be permitted on a standard capacitor.

This departure from a true sine wave of voltage results in an increase in the operating kva of the capacitor. Capacitor units therefore must have a thermal margin sufficient to allow for overvoltage and wave-form distortion. Either an increase in working voltage or the presence of harmonics or both can use up this margin. Any consideration of permissible harmonic components must of necessity be based on an assumed level of voltage.

An industry standard of 135 per cent has been established for many years to cover the permissible operating kvar of a capacitor unit. Capacitor units and auxiliary devices such as fuses and switches are designed to permit the capacitor to draw 135 per cent of its rated kvar, including kvar due to the fundamental voltage and all harmonic voltages.

In order to translate this 135 per cent into permissible excess normal current, it is necessary to know the harmonic voltage as well as the operating voltage.

$$\text{Kvar}_f + \text{kvar}_h = 135 \text{ per cent of rated kvar}$$

The kvar_f, or kvar at the fundamental frequency, and the kvar_h, which is the kvar at the harmonic frequency, can be determined only by knowing the actual voltage at the fundamental and the harmonic. This information is obtainable with a harmonic analyzer, which is nothing more than a voltage-measuring device equipped with filters to permit measuring only the fundamental-frequency voltage, or only the desired harmonic voltage. The total operating kvar of the capacitor is the sum of the kvar computed for each frequency and added arithmetically. When accurate information is desired harmonic analysis is desirable.

Where only one harmonic is involved, or at least where the others can be ignored, the total current and total voltage may be sufficient to determine if the 135 per cent limit is being exceeded, if one determines the prevailing harmonic. This may be done by observing the wave shape with an oscilloscope.

$$\text{Total rms current} = \sqrt{I_f^2 + I_h^2}$$

where I_f = fundamental frequency current
I_h = harmonic current.

$$\text{Total rms voltage} = \sqrt{E_f^2 + E_h^2}$$

where E_f = fundamental frequency voltage.
E_h = harmonic voltage.

The total rms voltage and total rms current may be read by using a conventional voltmeter and ammeter, and the 135 per cent permissible working kva can be expressed in terms of permissible total rms current in per cent of normal rms current. The normal rms current is the calculated current based on a sine-wave voltage and capacitor rated voltage.

Figure 12 shows the permissible measured rms currents based on measured rms voltage.

Consider the case of a 100-kvar three-phase 2,400-volt capacitor:

$$\text{60-cycle current at rated voltage} = \frac{100 \times 10^3}{2{,}400} \div \sqrt{3} = 24 \text{ amp}$$

$$\text{Measured rms voltage} = 2{,}415 \text{ volts (105 per cent)}$$

The capacitor would be expected to draw more current due to the 105 per cent voltage, but this will use up only a portion of the 135 per cent kvar margin. The permissible current will depend on the harmonic involved. Assuming it is the third, reference to Fig. 12 will show that the permissible current is 146 per cent.

146 per cent of 24 amp = 35 amp

If the measured rms current does not exceed 35 amp and if the harmonics other than the third are of negligible importance, it may be assumed that the capacitor is for all practical purposes operating within the 135 per cent kvar limit.

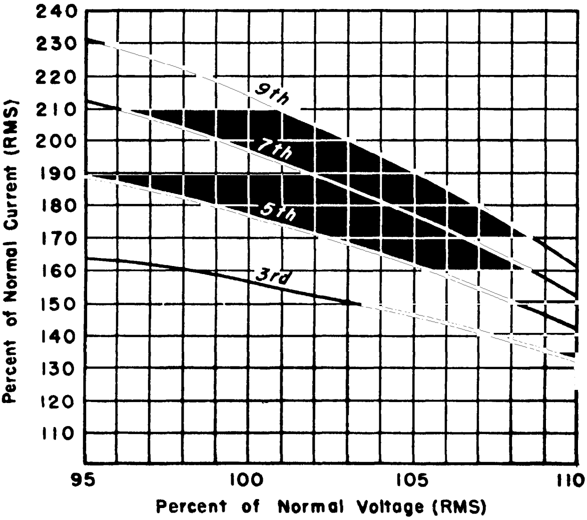


FIG. 12. Limits of excess current in capacitor units, based on thermal limit of 135 per cent of rated kvar.

If the predominating harmonic is high, such as the fifth, the permissible current is 38.4 amp; and if the seventh, the current may be 41.7 amp.

Ambient Temperature. All power-capacitor units are designed for an ambient temperature of 40°C (104°F), but some capacitors such as those rated for 230 volts and outdoor open-mounted units may be operated in an ambient temperature of 50°C.

When capacitor units are designed for higher ambient temperatures it is necessary to increase the amount of insulation and case surface so as to avoid exceeding the maximum safe internal working temperature.

This results in considerable increase in cost for a given rating in kvar. For this reason it is far more economical to reduce the ambient working temperature by ventilation or location of the capacitor than to use a special capacitor designed for higher than normal ambient temperature. In the design of capacitors low inherent losses and low temperature rise make it possible to work the insulation at high voltage gradients and thus obtain a high kvar rating per unit of weight, cost, and volume, without exceeding a safe internal working temperature for the insulation. If the ambient temperature is high, lower voltage gradients must be used, and the size and weight increased as the square of the reduction in gradient.

Where capacitor units are housed or assembled in racks, the ambient-temperature limit for the entire assembly is governed by the type of rack or assembly and the ventilation provided.

Intermittent Duty. Power capacitors are usually applied on the basis of continuous voltage, and this is associated with the temperature rise. When applied on an intermittent basis and on the basis of a duty cycle which will result in a relatively low equivalent continuous kvar, they may be operated at higher voltage. Two examples of this are capacitors connected in series with resistance welders and capacitors that are used only during the starting of motors. It is common practice to apply up to 150 per cent voltage in the case of series capacitors on a momentary basis, and up to 130 or 140 per cent in the case of motor starting depending on the nature of the intermittent duty.

Terminal-to-case Rating. The terminal-to-case working voltage is not intended to exceed the terminal-to-terminal rated voltage. Capacitors may therefore be connected line to ground when the voltage to ground corresponds to the terminal-to-terminal voltage rating of the capacitor and when the circuit voltage is solidly grounded. It is customary, however, to insulate the cases from ground by additional insulators and to star-connect the capacitors, leaving the neutral of the capacitor free in cases where the line neutral is ungrounded. Also several capacitor units may be operated in series, connected phase to phase or phase to ground when additional supporting insulators are properly used.

DESIGN AND MANUFACTURE OF POWER CAPACITORS

Paper. It was brought out in Chap. 1 that the most practical dielectric yet found for 60-cycle power capacitors is paper, impregnated and submerged in a suitable insulating liquid. Many centuries ago, when it was found that the bark of trees could be used to make a sheet-like material on which to record human thought, no one could have imagined that in advanced civilization a paper could be made thinner than a human hair and flawless, yet today large quantities of paper less than 0.00035-in. in thickness are used in capacitors. Most power capacitors, however, make use of 0.0005-in. paper. The problem of manufacturing even 0.0005-in. paper in a closed sheet and almost entirely free from holes and conducting particles is undoubtedly the most difficult operation in the art of papermaking. In addition to these physical requirements the paper must be quite free from foreign chemical substances that are soluble in the impregnating fluid and which might lower the quality of the finished product.

Capacitor paper is made in rolls usually 80 or 90 in. wide and is later cut into narrower widths, after which it is calendered under high pressure to produce a smooth, dense sheet. After calendering it is cut into widths suitable for use in the manufacture of capacitors.

One of the most important characteristics of the paper which affects the design and performance of the capacitor is the number of conducting particles or flaws per unit of area.

In a paper presented at the Summer Meeting of the A.I.E.E., June, 1947, Hamilton Brooks showed that the frequency of occurrence of defects of this kind in capacitor paper follows the Poisson law of probability. He showed by statistical evidence that large conducting particles exist in the paper and may bridge one or more layers of paper in the finished capacitor through chance orientation caused by manufacturing processes and operations.

Because of this possibility constant efforts have been made to reduce the number of conducting particles to a minimum by testing samples of paper and by specifying permissible limits for conducting particles per square foot.

When the manufacture of power capacitors had just begun it was not uncommon to find several hundred conducting particles in each square foot of 0.0005-in. paper. Today this is held below 3 particles per square foot. Such tests are made by passing a roller over a sheet of paper supported by a flat metal plate and counting the clicks in a telephone receiver in a circuit which is completed by flaws in the paper. Figure 13 shows a setup for this test.

The paper is also tested for porosity. It is important that the sheet be well closed. This test is made by measuring the quantity of air that will flow through the paper under a standard pressure differential. This test is illustrated in Fig. 14.

Another important property of paper is density. If the density is too high the losses will be slightly increased. If it is too low the breakdown voltage will be lowered, and the capacitor will be less able to stand high transient voltages and switching surges.

The density is measured by weighing a given volume of paper in the dry state (see Fig. 15).

FIG. 13. Testing capacitor paper for conducting particles.

Foil. Next to paper in importance is the foil used to form the electrodes in the capacitor sections. At first tin or lead foil was used for this purpose but the availability of pure aluminum, which can be rolled into thin sheets, soon made it possible to produce aluminum in thicknesses of 0.00025 and 0.00035 in. In addition to its lightness aluminum has the advantage of being relatively inert in contact with other materials used in capacitors such as mineral oil and synthetic impregnants. Practically all power capacitors are now manufactured with aluminum foil. Even during the Second World War, when aluminum was much in demand, no satisfactory substitute could be found for use in paper capacitors.

Figure 16 shows one operation in the manufacture of aluminum foil. The remarkable progress made in the manufacture of aluminum foil is

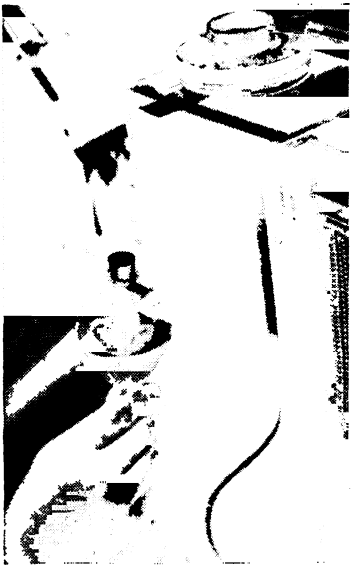


FIG. 14. Testing capacitor paper for porosity.

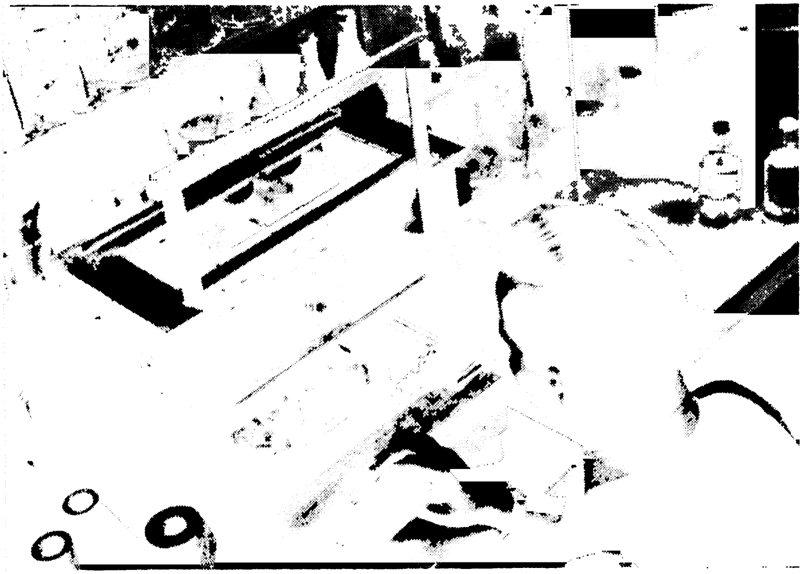


FIG. 15. Testing capacitor paper for density.

illustrated by the fact that during the war large quantities of foil were made with a thickness of 0.00017 in. for war purposes and communications capacitors.

Capacitance Calculations and Voltage Stress. The number of layers used to separate the foils in a single capacitor section is governed by numerous design factors. A typical 230-volt section used in a 7½-kva capacitor unit is made of three layers of 0.00035-in. paper separated by 0.00025-in. foil. This gives a working stress of 220 volts per mil, neglecting the liquid film, whose thickness is determined by assembly pressure. Capacitors for 460 volts are usually worked at higher stresses. A typical 15-kva 460-volt capacitor section is made up with three layers of 0.0005-in. paper giving a nominal stress of 305 volts per mil.

FIG. 16. Manufacture of aluminum foil for capacitors.

A 2,400-volt 15-kva unit may consist of two groups of 1,200-volt sections connected in series, each 1,200-volt section consisting of seven layers of 0.0005-in. paper giving a stress of 345 volts per mil.

Higher voltage capacitors are usually made up of series-connected groups with the voltage rating of each group not exceeding 1,200 volts.

The total area of dielectric required is determined by the capacitance required and is dependent on the thickness of the dielectric, dielectric constant, pressure of final assembly, and other factors, such as the density of the paper.

Consider the case of a 15-kvar 2,400-volt capacitor unit treated with pentachlorodiphenyl and with a nominal voltage stress of 345 volts per mil.

$$\text{Total capacitance} = \frac{\text{kvar} \times 10^3}{E^2\, 2\pi f \times 10^{-6}}$$

$$\frac{15 \times 10^3 \times 10^6}{5.76 \times 6.28 \times 60}$$

$$= 6.91\ \mu\text{f}$$

Adding 7.5 per cent allowance for manufacturing variations, this becomes 7.43 μf. Since the capacitor will consist of two groups in series, each group must have a capacitance of 14.86 μf. If the capacitor is made up of twelve sections, each 14.86-μf group will consist of six sections in parallel and each section must have a capacitance of

$$\frac{14.86}{6} = 2.47\ \mu\text{f}$$

The area of dielectric is now determined by the use of the simple relation

$$A = C \times T \times K$$

where A = total active area of the dielectric, sq in.
C = capacitance, μf.
T = thickness of dielectric, mils.
K = empirical factor, which includes average assembly pressure, dielectric constant, fluid film, and paper density (a typical value is 1,000).

$$A = 2.47 \times 3.5 \times 1{,}000 = 8{,}645 \text{ sq in.}$$

Winding Sections and Assembly in Case. In winding a capacitor section two dielectrics and two foils are wound up on the mandrel with one dielectric between the foils and one on the outside of one foil, so that a foil will always be adjacent in either direction to a dielectric. Therefore the wound length of the section is one-half the total length of dielectric.

The active width of the dielectric is the area common to both foils. Assuming foil 9 in. wide and a total active area of 8,645 sq in., the length of the winding will be

$$\frac{8{,}645}{9 \times 2 \times 12} = 40 \text{ ft}$$

To set up for winding the above section, 14 rolls of paper and two rolls of foil are arranged on mandrels. One set of seven sheets of paper is first started, then one foil, then a second set of seven sheets of paper, and then the second foil. When all paper and foils are started the winding must proceed until 40 ft of travel occurs, or 40 ft for each foil.

Figure 17 shows a typical winding machine as used for a capacitor section.

FIG. 17. Winding capacitor sections.

The paper used in winding a capacitor section is wider than the foil to provide adequate margins for the prevention of flashover from foil to foil. During the winding operation the winding machine is stopped to permit insertion of tinned copper strips for making contact with the foils and providing a means of external electrical connection.

Figure 18 shows an operator preparing to hand-press a section into a flat form. A group of such sections is shown in a stack with their tabs extending.

Figure 19 shows an operator preparing to assemble a group of sections into an insulating frame to make a final assembly for a 15-kvar capacitor.

After the capacitor sections are assembled in the case (Fig. 20) a

FIG 18 Preparing capacitor sections for assembly

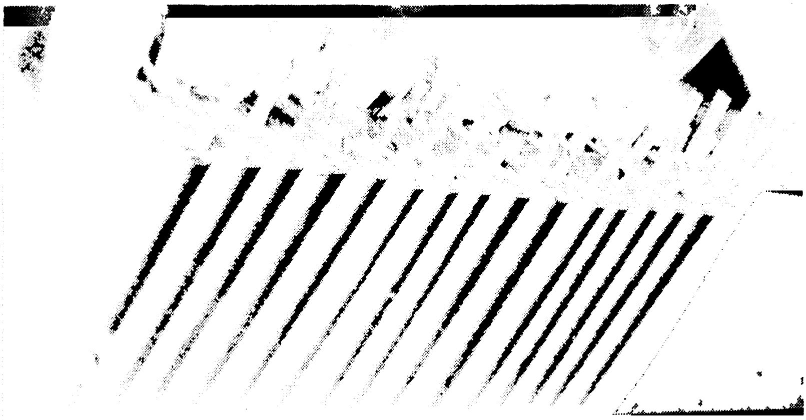


FIG 19 Assembling capacitor sections in insulation barriers to produce a 15-kvar capacitor

test for capacitance is made to determine if the capacitance is of the required order. The final capacitance cannot be accurately predicted from the capacitance as measured on the undried capacitor but this test is sufficiently accurate to warn the operator of errors in assembly or connections.

FIG. 20. Preliminary capacitance check before welding on cover.

In a gas-welded capacitor the next operation consists of welding on the cover. This is done in a manner to avoid damage to the internal element. Figure 21 shows the operation being performed.

Processing. The processing operation consists of removing not only the free moisture from the paper and other insulating material but removing some of the closely held water. This latter operation requires considerable heat and time and the entire process requires much longer than required merely to remove the free water. The time is also governed by the path through which the moisture must flow. Large power capacitors are therefore much more difficult to process than small radio capacitors. Figure 22 shows a set of 15-kva capacitors being loaded into a processing oven. In the sealed compartment the temperature will be raised to approximately 135°C and the pressure will be reduced to a very small fraction of atmospheric pressure. After the capacitors have given up water to a sufficient degree, they are saturated and filled with the impregnating fluid, which has been prepared and stored in the tanks shown above the ovens during the drying stage.

Fig. 21. Welding case cover.

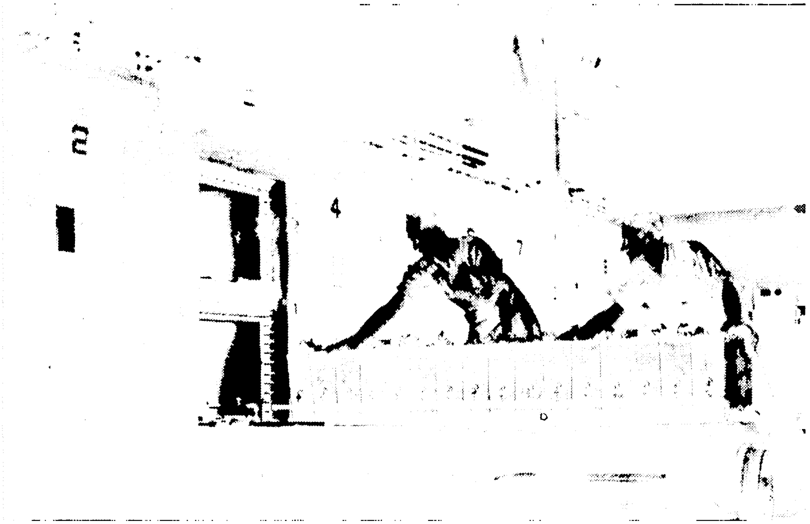


Fig. 22. Loading units for drying and impregnating.

The impregnating fluid is prepared by the use of activated clay to reduce the moisture content to a few parts per million and to remove other impurities which would effect losses in the completed capacitor.

The capacitor is not exposed to the atmosphere until after it is filled with the fluid and the working insulation is completely covered. After the terminals are mounted, the unit is completely filled and sealed.

Terminals. Various types of terminals have been used to provide a tight seal and prevent entrance of foreign matter. One of the most successful types consists of a porcelain body bearing a metallized surface to which solder can be applied, producing a truly soldered seal. This type is shown in Fig. 23. Both the top cap and the base ring are soldered direct to the porcelain body.

The porcelain is first manufactured complete with the glaze. Next, metallic bands are applied by painting with a solution containing platinum and other metallic compounds, after which it is fired. When removed a bright metallic band has been produced This band is tinned with solder to prepare for soldering the base ring and cap.

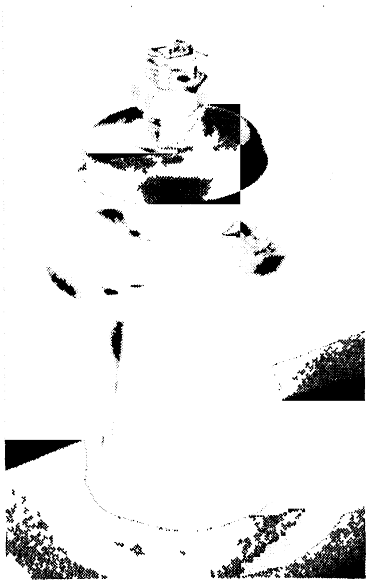


FIG 23 Terminal for 2,400-volt capacitor (outdoor solder-seal type).

FIG. 24. Applying metallic paint to porcelain.

Gasket-sealed terminals have also been used commercially on large capacitors but a certain percentage leak due to temperature cycles and handling. The solder-to-porcelain type has proved to be the solution of this problem and millions of such terminals have been used over the past 13 years.

Cleaning and Finishing. After the capacitors are sealed they are subjected to a cleaning operation to remove impregnating fluid and they are tested to insure freedom from fluid leaks. This consists of placing them in an oven at a temperature of 85°C for a period of 5 to 8 hr. Leaks are discovered more quickly by coating the surface with a porous water paint. Once free from leaks the capacitors are again cleaned and given the final finish.

FIG. 25. Loading porcelains in oven for firing metallic paint

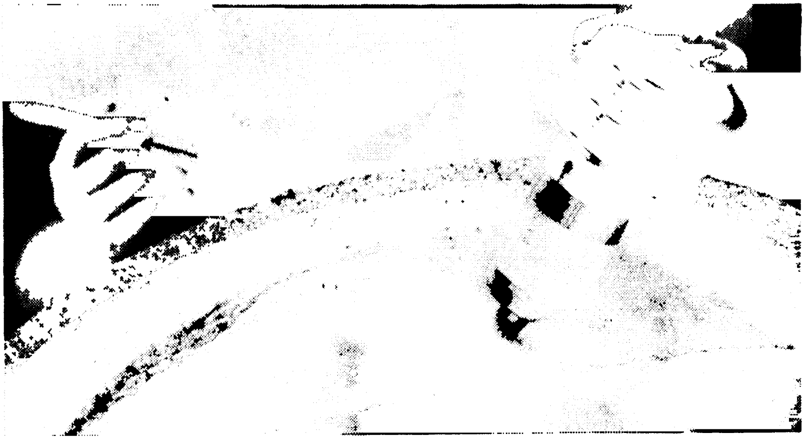


FIG. 26. Tinning metallic band on porcelain

The finish applied to a capacitor, as to other equipment, is determined by the requirements of appearance, matching other equipment, or protection. Indoor capacitors require very little protection when they are actually mounted inside. Many so-called indoor capacitor units are housed in steel enclosures which are located outdoors. Some moisture can reach these capacitors through the ventilators, which are necessary for the circulation of air in hot months. It is desirable, therefore, for indoor power-capacitor units to be well protected against rusting.

FIG. 27. Soldering metal fittings to the metallic bands.

FIG. 28. Mounting porcelains on capacitors

Outdoor capacitors present a very definite problem of rust prevention. Paint has been used on many outdoor capacitors but regardless of the grade of paint or method of application, repainting is necessary at intervals. Since capacitors are usually mounted only 1 to 1½ in. apart, it is impossible to paint them satisfactorily in position on the pole or mounted in a housing.

A type of finish used extensively to solve the problem of frequent refinishing is metallizing the surface. Almost any metal that can be melted with an acetylene torch can be sprayed on, but metal coatings do not give corrosion protection unless they are anodic electrically to the base metal. No complete sealing is then necessary. Aluminum and zinc are the two metals most satisfactory for spraying over steel for protection against atmospheric corrosion.

Where salt atmosphere is encountered the zinc coating should be much heavier, since a considerable quantity of the zinc is used up in the first few months until the pores become sealed with zinc salts. After this there is very little further action. Very thin zinc coatings such as are obtained by hot-dipped galvanizing, which are 0.001 to 0.0015 in. thick, do not stand up well in salt atmosphere; but when zinc is sprayed on in liberal layers of 0.01 to 0.012 in., long life is obtained even under very severe salt fog conditions. A minimum life of 7 years may be expected with a coating of 0.006 to 0.008 in. and 15 years with a coating of 0.01 to 0.012 in. in salt atmospheres. These periods are much longer under average atmospheric conditions. Where capacitors are sprayed with zinc, the coatings used are 0.01 in. average.

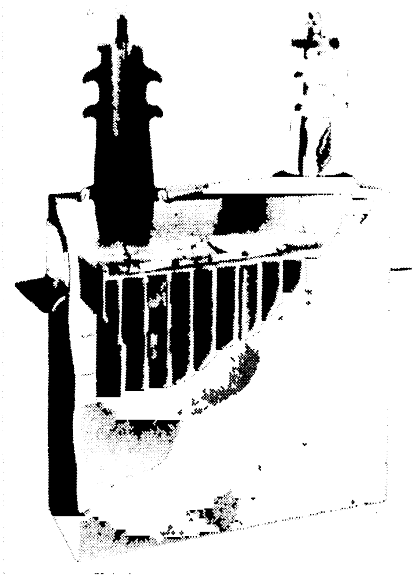


FIG. 29. Fifteen-kva 2,400-volt outdoor capacitor (cut away).

Figure 29 shows a 15-kvar 2,400-volt outdoor capacitor cut away to show the internal arrangement of parts. This capacitor has two groups connected in series, with each group containing six sections in parallel. A discharge device is built into the capacitor consisting of three special ceramic resistors of 2.5 megohms each, connected in series to total of 7.5 megohms, which is connected from one terminal of the capacitor to the other. This resistor will discharge the capacitor to 50 volts or less five minutes after the capacitor is disconnected from a source of potential, and it will prevent any harmful residual voltage from building up

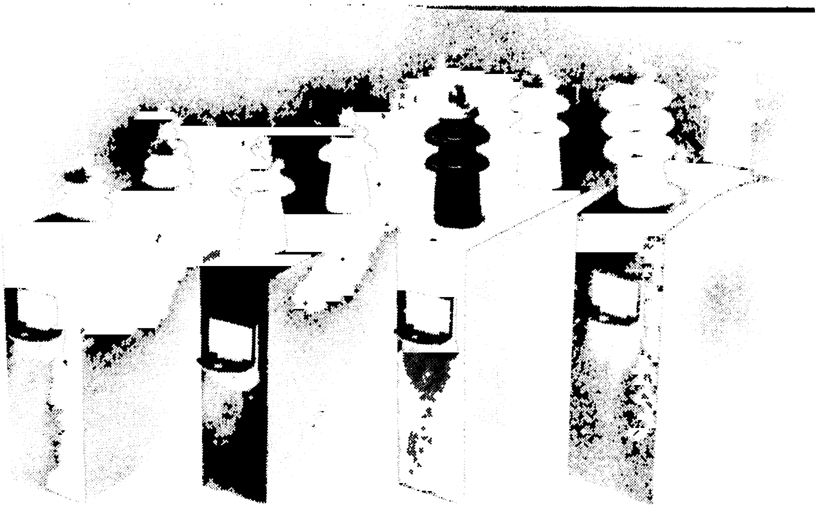


FIG 30. Fifteen-kva 460-, 2,400-, 7,960-, and 13,800-volt outdoor capacitors.

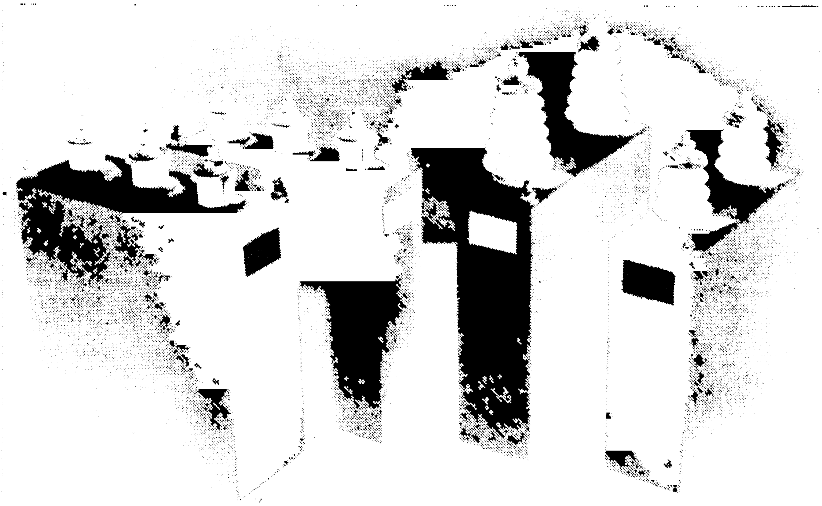


FIG. 31. Indoor capacitor units of 230 volts, 7½ kva; 460 volts, 15 kva; 7,960 volts, 15 kva; and 2,400 volts, 15 kva.

across the capacitor terminals. The National Electrical Code requires that all a-c power capacitors be provided with an automatic discharge means which will discharge capacitors rated above 600 volts in five minutes and those rated 600 volts and below in one minute.

Figure 30 shows a group of 15-kva outdoor capacitors for 460, 2,400, 7,960, and 13,800 volts; Fig. 31 shows a group of indoor capacitor units. Those in both Figs. 30 and 31 are metalized with zinc.

Testing. Tests consist of applying an overpotential between terminals and between terminals and case, and a check on capacitance and power loss at rated voltage and frequency A built-in discharge resistor is used in each capacitor unit to discharge the capacitor to a safe value each time it is disconnected from the circuit. A test is made to check the effectiveness of this resistor.

TABLE 7 CAPACITOR TEST VOLTAGES

Voltage rating of 60-cycle capacitor, kv	Voltage test between terminals, kv	Terminal-to-case test voltage, kv		Terminal-to-case impulse test, crest kv
		Indoor	Outdoor	
0.23	0.5	3	10	30
0.46	1	5	10	30
0.575	1.2	5	10	30
2.4	5	19	19	60
4.16	9	19	19	60
4.8	10	26	26	75
7.2	15	26	26	75
7.96	16.6	26	26	75
12.47	25	34	34	95
13.80	28.8	34	34	95

Table 7 gives typical test values that have been adopted by the electrical industry for power capacitors.

The voltage test between terminals and terminal and case is made at 20 to 70 cycles for a duration of one minute.

The impulse test is made with a 1.5–40-μsec wave.*

The losses are measured at rated voltage and frequency and are held to a maximum of 3⅓ watts per operating kvar based on an ambient temperature of 25°C.

Test are also made on designs to insure freedom from radio interference and compliance with standards set up by the industry.

---

* The 1.5–40-μsec wave is one that rises from virtual zero to crest voltage in 1.5 μsec and has a time of 40 μsec from virtual zero to half of crest value on the wave tail.

Bibliography

BROOKS, H.: The Probable Breakdown Voltage of Paper Dielectric Capacitors, *A.I.E.E. Trans.*, pp. 1137-1144, 1947.

BROOKS, H., and B. EPSTEIN: The Theory of Extreme Values and Its Implications in the Study of Dielectric Strength of Paper Capacitors, *J. Applied Phys.*, June, 1948.

CHAPTER 3

INDUSTRIAL, HIGH-FREQUENCY, AND D-C POWER CAPACITORS

CAPACITORS FOR INDUSTRIAL POWER CIRCUITS

Although very small capacitors are sometimes used directly connected to small loads or combined with a piece of equipment to raise the over-all power factor, these cases are limited to special applications and will not be discussed. It is not generally worth while to apply power-factor correction directly to motors or other loads using less than 5 or 10 kvar when the purpose is to relieve the line of supplying kvar, because of the fact that the cost per kvar increases rather rapidly when small capacitors are used. Sometimes there are special reasons for using the small capacitors, as, for example, in the case of the capacitor motor. Here the purpose of the capacitor is to cause a phase displacement in one of the motor windings. It is used primarily for this reason, and the fact that the resulting device has relatively high power factor is secondary. Capacitor motors therefore may use very small capacitors and ones that are not to be classified as power capacitors.

Where the chief purpose is power-factor correction, direct-connected motor capacitors are seldom less than 5 kvar for 230-volt motors or less than 10 kvar for motors of higher voltages. These capacitors are usually arranged for easy mounting beside the motor and are arranged with a protective cover over the terminals, which acts as a junction box for armored cable or conduit. These covers or connection boxes often contain space for fuses. Figure 32 shows a group of enclosed dust-tight capacitors of this type.

Where the individual loads or motors require larger capacitors made up of several 15-kvar capacitor units, these are assembled so as to enclose the terminals, fuses, and other live parts and provide means for connection to conduits. Figure 33 shows a group of typical dust-tight assemblies containing two, four, six, and eight 15-kvar units for 460- or 575-volt 60-cycle three-phase applications. When these are for 230-volt circuits, they are made up with 7½-kvar units. Assemblies for this kind can be stacked three high giving banks of 45, 90, 135, and 180 kvar for 230 volts where 7½-kva units are used or 90, 180, 270, and 360 kvar where 15-kvar 460- or 575-volt units are used.

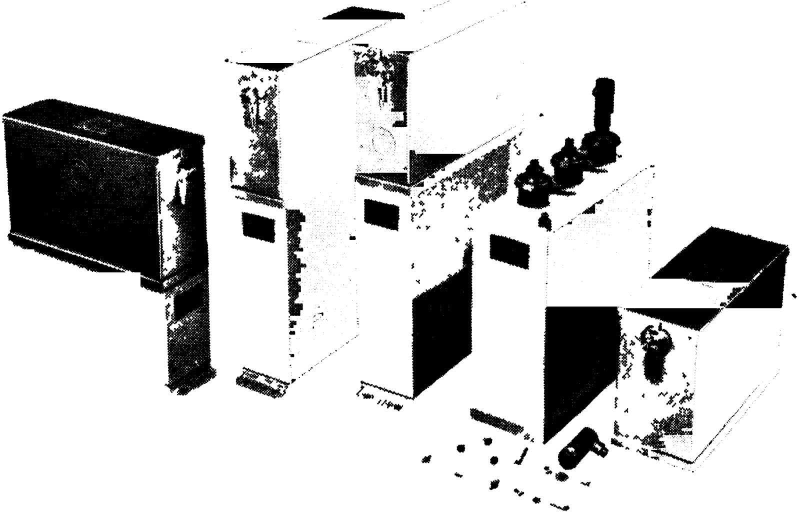


Fig. 32. Enclosed dust-tight individual capacitor units.

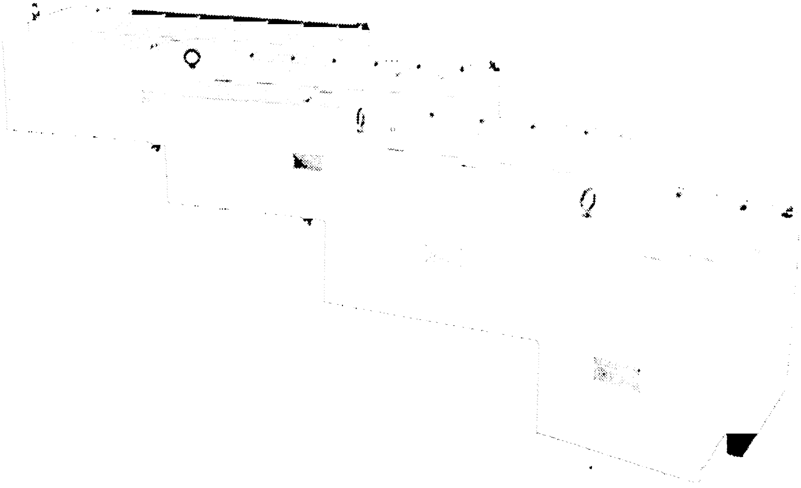


Fig. 33. Multiple dust-tight capacitor assemblies.

The capacitor units used in either the single- or multiple-unit assemblies, Figs. 32 or 33, are of the indoor type as shown in Fig. 34.

Indoor capacitor units are also made up for voltages up to 13,800. Figure 35 shows a 7,960-volt 15-kva indoor unit.

For 2,400 volts and above, larger size banks of capacitors are usually required, and in most cases a circuit breaker is combined with each assembly of capacitor units. On the lower voltages, such as 230 to 460 volts, breakers are also assembled with the capacitor units. These assemblies are made up for from 360 to 2,520 kvar. The maximum size is limited to 2,520 kvar for convenience in handling. A typical installation may contain any number of such banks, each with its own circuit breaker or with only one externally mounted breaker to handle the entire group. These assemblies or capacitor housings are often made weatherproof so that the capacitor may be located outside where space is less at a premium.

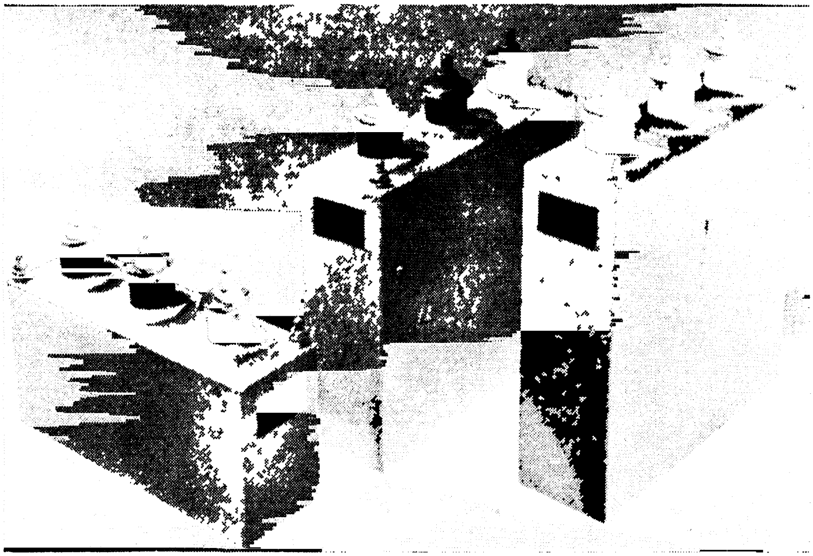


FIG. 34. Indoor 230-, 460-, or 575-volt, three-phase capacitor units.

Figure 36 shows a typical large capacitor housing for 13,800-volt service.

In the case of large capacitor assemblies for 230 to 2,400 volts, single-phase capacitor units are normally used and arranged in three delta-connected groups. They may be delta connected for 4,160 to 7,960 volts also; however, two problems arise which make it desirable to Y-connect the units, one being the fault current, and the other the cost of insulating the capacitor units for the full voltage. If the fault

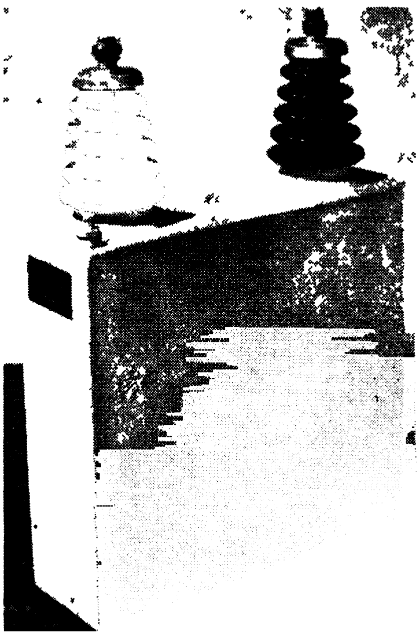


FIG 35 Fifteen-kva, 7,960-volt indoor capacitor unit.

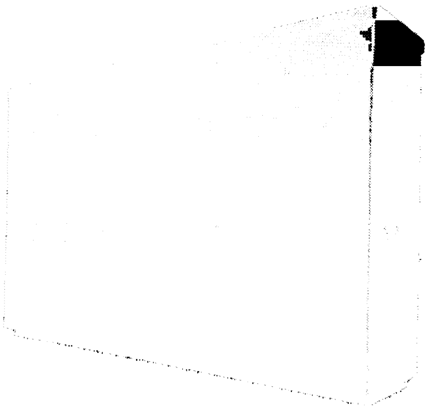


FIG. 36 Large outdoor housed capacitor.

current is likely to be high, a more expensive individual fuse is required, such as a current-limiting fuse or a fuse with high interrupting capacity. If the units, however, are Y-connected, as, for example, 2,400-volt units for 4,160-volt service, and if the capacitor neutral is left floating, a fault in one capacitor unit will draw only a limited amount of fault current that is well within the limits of an inexpensive individual fuse.

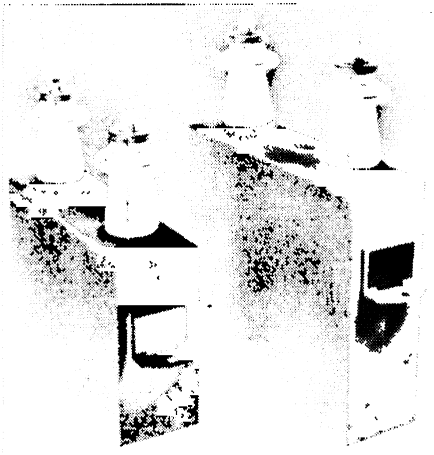


FIG. 37. Ten- and 15-kva, 2,400-volt outdoor capacitor units.

If a 13.8-kv bank of capacitors is made up of 7,960-volt capacitors with neutral floating, two advantages are obtained, the one being the limited fault current and the second being the lower cost of the units. It is more economical to provide some of the insulation in the form of apparatus insulators to support the 7,960-volt units in the rack than to provide 13.8-kv insulators on each one of the capacitor units, and the over-all dimensions of the complete housing are also reduced.

Outdoor capacitor units are quite similar to indoor units except for the means provided for mounting and the terminal bushings. The outdoor units are usually arranged with mounting lugs and the porcelain terminals are larger to allow for wet-flashover requirements and bad atmospheric conditions. When atmospheric conditions are exceptionally bad, as in areas where salt fog is troublesome, even larger insulators are needed, as with other electrical equipment. Figure 37 shows 10-kvar and 15-kvar 2,400-volt outdoor capacitors.

Outdoor capacitor units were first used to provide a convenient means of adding capacitors to distribution circuits, particularly where no space was available except on the pole crossarm. A typical installation of this kind is shown in Fig. 38. A total of twelve 2,400- or 4,160-volt 15-kvar units may easily be placed on one pair of crossarms.

Where a large amount of kvar is required, and particularly where the voltage is above 13,800, the outdoor capacitor units are often connected in series parallel and insulated by supporting insulators to provide banks of 2,500 kva or more in a manner as shown in Fig. 39. This is a 24,000-volt installation totaling about 10,000 kvar, used to supplement a synchronous condenser.

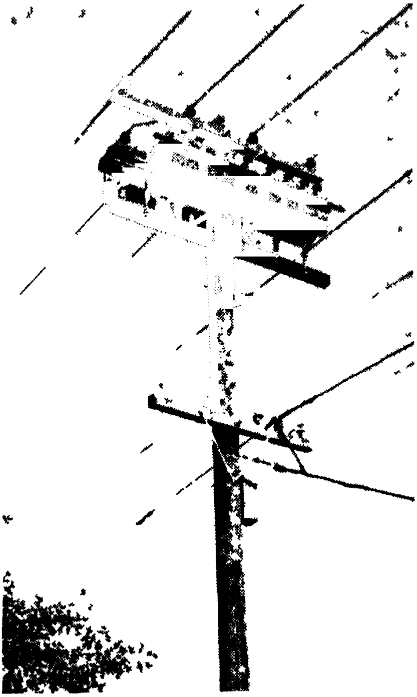


FIG. 38. Pole-mounted, 135-kva bank of outdoor capacitors on a 4-kv circuit.

CAPACITORS FOR HIGH FREQUENCY

Where the frequency is below 12,000 cycles, paper capacitors have been used quite extensively.

In the lower frequency range, such as 120 to 180 cycles, used for high-speed woodworking, grinding, and spinning motors, the capacitor is almost identical in construction to 60-cycle capacitors. If the cooling is by natural air circulation the 60-cycle kvar ratings are held and the capacitors are designed internally so as to operate at these same kvar ratings at the particular voltage and frequency specified.

Since at high frequency higher kvar ratings are possible with the same voltage stress on the dielectric, provided the heat loss can be removed effectively by forced cooling. Forced-air cooling makes it possible to design capacitor units with approximately double the normal 60-cycle kvar rating.

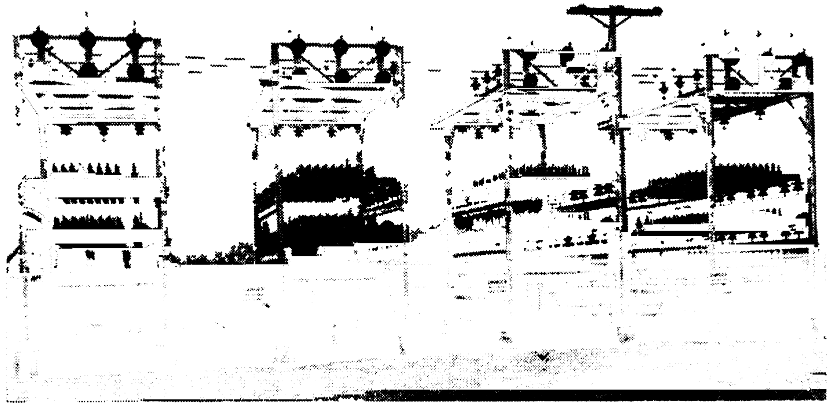


FIG. 39. Ten-thousand-kva, 24,000-volt substation bank using open-mounted outdoor units.

The kvar can be still further increased by more water cooling. For a frequency above 500 cycles, where cooling water is available, as is the case with induction-furnace installations, special capacitors have been designed in which the dielectric voltage stress is the same as for 60 cycles. On a frequency of 2,000 cycles this makes it possible to build a 300-kvar capacitor occupying the same space as a 60-cycle 15-kvar unit. In such a unit, the losses are approximately 1 to 1¼ kw, but efficient designs with water circulating through copper tubing soldered directly to the capacitor foil edges make it possible to remove almost all of this heat and thus keep the maximum dielectric working temperature down to about the same value as the dielectric in a 15-kvar 60-cycle natural-cooled unit. The quantity of water used for each 300-kvar unit is not over a gallon per minute, and several 300-kvar units can be cooled with a gallon-per-minute flow through the group if the initial temperature of the water permits. The outgoing water is usually held to 30°C or below and the rise in water for each 300-kvar unit is only a few degrees centigrade. Where the initial water temperature is higher the water must pass through each unit separately. Where the temperature of the available cooling water is still higher and it is difficult to keep the outgoing water temperature to 30°C or below, it is necessary to limit the working voltage of the capacitor to some value below rated voltage. For each degree above 30°C the applied voltage must be reduced 1.5 per cent in order to reduce the operating kvar of the capacitor and the internal loss to compensate for the less effective cooling.

In such high-frequency capacitors the problem of handling the current through the terminals is easily solved by liberal-size studs when the voltage is 600 or above. Where lower voltages are involved, the current may become the limiting factor due to eddy-current losses set up in the cover of the capacitor. Capacitors rated at 300 kva have been made for 440 volts by using nonmagnetic material for the capacitor case and cover, and by using several terminals to handle the total current.

Since the copper cooling tubes must be soldered directly to the capacitor foils it is usually the practice to bring these tubes out through bushings in the case and thus make the case common to one terminal of the capacitor. This usually means that the case must be supported on insulators and the water connections insulated by inserting short lengths of rubber hose between water connections which are not at the same potential.

Figure 40 shows a 300-kva 1,250-volt 2,000-cycle water-cooled capacitor of the type described, which internally consists of two 625-volt groups in series with the midpoint grounded to the case through the water-cooling system.

Figure 41 shows a typical unit of the low-voltage type in which several terminals are used to carry the total current and the case and cover must be made of nonmagnetic material.

In the design of high-frequency capacitors several points must receive special consideration. Tabs cannot be used to make connections to the foil due to the large current. For this reason, all high-frequency capacitors of the types described are wound with the foil edges extending beyond the paper so that the entire edge may be used for a current-carrying connection. In addition to the current problem there is the problem of handling the heat. For each cubic inch of working dielectric the dielectric loss is twenty times as great as in a 60-cycle capacitor due to the large kvar rating per unit. This heat must be transferred to the water through the foil path. The cross section of the foil path and the length of the path must receive careful consideration in order to control

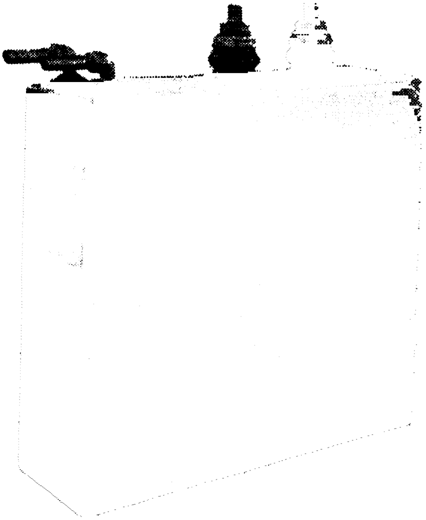


FIG. 40. Three-hundred-kva, 2,000-cycle, 1,250-volt water-cooled capacitor.

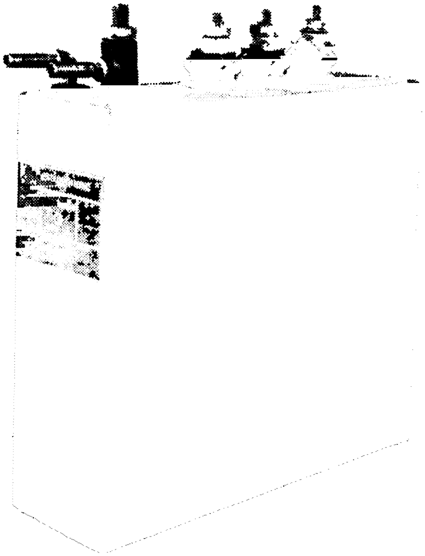


FIG. 41. Three-hundred-kva, 625-volt, 2,000-cycle water-cooled capacitor.

the temperature gradient. This necessitates either using very heavy foil or a very short foil heat path. Copper foil has sometimes been used because of its high conductivity which permits a longer heat path, or wider capacitor section.

Figure 42 shows an installation of 48 water-cooled high-frequency capacitors on a 960-cycle induction furnace.

CAPACITORS FOR D-C SERVICE

Direct-current service is intended to cover a type of service where the voltage is predominantly unidirectional and where any ripples present are of negligible magnitude and therefore produce no appreciable heating of the capacitor. In some so-called d-c applications, however, the a-c component is so important that it determines the selection of the capacitor rather than the d-c component.

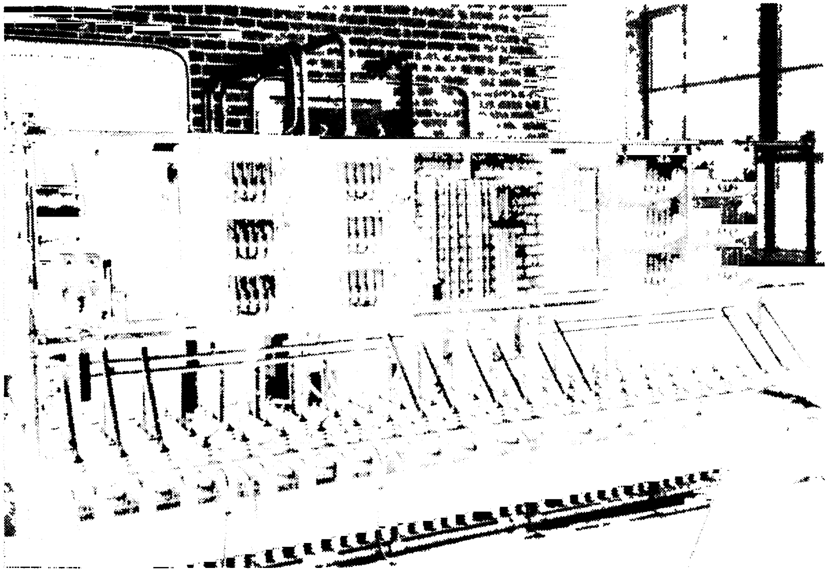


FIG. 42. Installation of water-cooled capacitors for 960-cycle induction furnace.

Direct-current service must be divided into several classes due to the widely different conditions and requirements. These are enumerated as follows:

1. Electronic applications such as filters for plate-circuit supply.
2. Direct-current power service.
3. Energy-storage applications.

The designs of d-c capacitors for the various types of service differ largely in ratings, voltage stress on the dielectric, and, in some cases, the service-life basis.

Electronic Capacitors. In d-c electronic applications, it is common practice to work the dielectric at stresses from 1,000 to 1,100 volts per mil, except for the voltages below 2,000, where the stress is dropped off to somewhat lower levels due to the extremely thin dielectric and large areas, involving probability of flaws. For example, a 600-volt d-c transmitting capacitor may contain three layers of 0.0003-in. paper giving a stress of 665 volts per mil. Even though the stress range of 665 to 1,100 volts per mil is higher than $\sqrt{2}$ times the equivalent 60-cycle rating of the dielectric, the life of d-c capacitors so rated is quite satisfactory. This higher stress on d-c service is possible due to the absence of appreciable heating. If the d-c capacitor is to be used in high ambient temperature, these high stresses are not practical. Industry standards base d-c ratings for transmitting capacitors on 40°C and show the derating necessary for ambient temperature above 40°C. For an application involving high ambient temperature, as for example a capacitor submerged in oil with a transformer, one has only to choose a higher voltage capacitor to start with so that after derating it will be capable of operating at the desired voltage.

FIG. 43. High-voltage d-c capacitor used with rectifier filters.

The change in capacitance with temperature is important on some special applications and must sometimes be taken into account. Capacitors of either the pentachlorodiphenyl or castor-oil types or those containing other dipolar inpregnants change with temperature more than those impregnated with mineral oil or similar liquids. These variations are not significant at temperatures above 0°C. It is therefore not necessary to consider these capacitance variations except in outdoor applications.

Direct-current capacitors intended for electronic service are not equipped with internal discharge resistors, and the high-voltage units must therefore be handled accordingly; however, after being installed they are usually discharged automatically through parallel-connected equipment and are therefore safe.

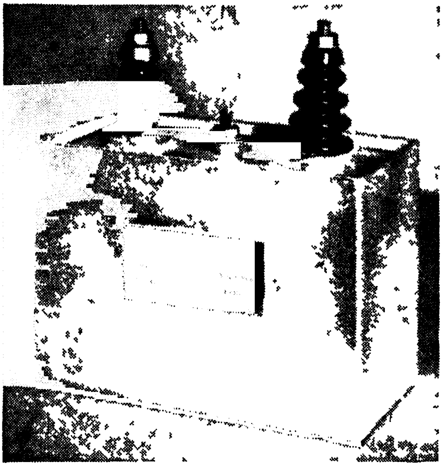


FIG. 44. High-voltage d-c capacitor used in the voltage-doubling circuit of a dust precipitator.

Figure 43 shows a group of large d-c capacitors used for d-c filters on tube-type rectifiers.

One common application for d-c capacitors of the type described is for making possible a voltage-doubling rectifier. Such rectifiers are used in the collection of dust by electrostatic precipitation. Figure 44 shows a capacitor designed especially for such service.

Direct-current Power-circuit Capacitors. In the case of d-c capacitors intended for connection to d-c power circuits, the design is quite different. The working stress is rarely higher than $\sqrt{2}$ times the equivalent 60-cycle rating, the insulators are rugged and liberal in creepage, and often the size of the capacitor is determined by factors other than the d-c voltage. For example, a capacitor used in a filter for a d-c power-rectifier circuit is selected on the basis of harmonic kva rather than d-c voltage.

A capacitor connected to a 600-volt railway trolley circuit may contain dielectric suitable for 4,000 volts d-c since the capacitor is designed to stand the lightning surges it is likely to be subjected to in service.

Most d-c power-circuit capacitors resemble 60-cycle indoor power capacitors because they are made of the same parts. Special-purpose d-c power-circuit capacitors have often been made. A typical example is a capacitor used for 600-volt railway service as shown in Fig. 45.

Capacitors for Energy Storage. Where energy storage is involved, the dielectric is worked harder than in the usual electronic application for several reasons.

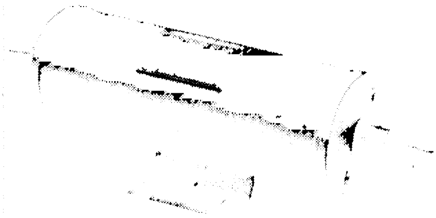


FIG. 45. Six-hundred-volt d-c railway-circuit capacitor for surge protection.

1. Minimum size at some sacrifice in life for the sake of space or portability.
2. Minimum first cost where duty is light.

Examples of energy-storage applications are as follows:

1. Surge generators for producing high-voltage discharges for investigation of the effects of lightning and testing apparatus for ability to withstand lightning surges.
2. X-ray equipment for photographing moving objects.
3. High-intensity flashes for photography.
4. Energy-storage welding.

The first important large-scale use of stored energy in capacitors was in the surge generator, one design of which is shown in Fig. 46. Here a number of $\frac{1}{4}$-μf 100-kv capacitors (Fig. 47) are charged up in parallel and allowed to discharge in series. Surge generators have been made to produce several million volts, with energy of 30,000 watt-sec or more.

In these capacitors the insulation has been worked as high as 1,500 volts per mil, giving more than twice the energy per unit as would be the case if they were designed with the same stress as radio-transmitting filter capacitors. The service is not severe due to limitations in discharge current and relatively infrequent operation because of the time required for recharging after each discharge. The annual replacements are not unreasonable since they rarely exceed one per hundred units used.

In X-ray application, the service must be more frequent, and the factor of continuity of service warrants the use of capacitors with somewhat more moderate stress. A stress of 1,100 to 1,250 volts per mil has been common practice; however, some derating is applied where the capacitors are associated with heat-producing equipment, as, for example, when mounted under oil in the transformer tank. In other respects, these capacitors are similar to surge-generator capacitors. A typical capacitor used for X-ray equipment is shown in Fig. 48. A group of such capacitors is charged up to a high voltage and then discharged through the X-ray tube giving a very intense beam of X rays for a very short duration.

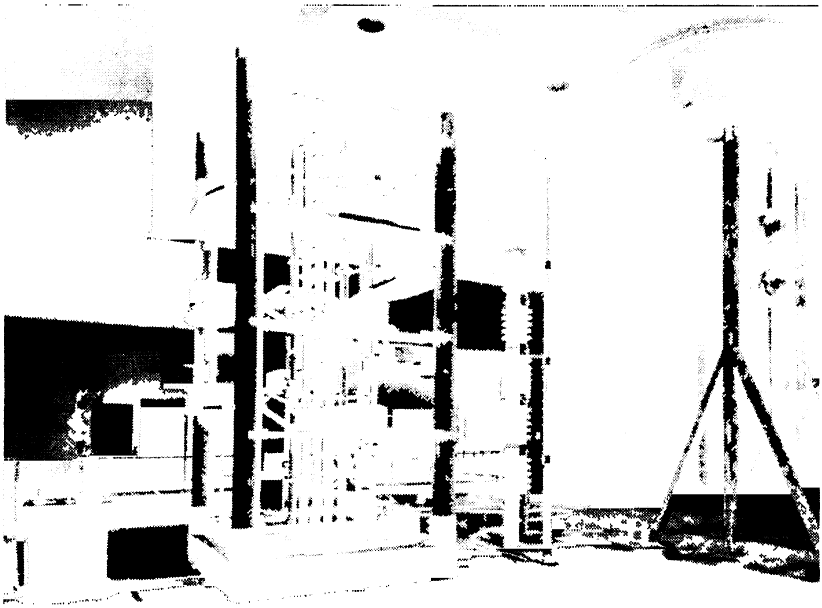


FIG. 46. Surge generator.

Energy stored in capacitors may be discharged through an incandescent lamp for producing high-intensity flashes for photographic purposes. The more common practice is to use a vapor discharge tube, however. Applications of capacitors in this manner run all the way from snapshot photography of fast-moving objects to high-intensity lighting of markers on airports. A very intense light can be produced in this manner, which is visible through considerable fog.

In the smaller capacitor application, capacitors for flash photography have often been worked up to 1,500 to 2,000 volts per mil where only about 10,000 flashes are expected from the capacitor and where considerable time will elapse between operations. In the larger applications, more conservative capacitor applications are made due to the repetitive service and the need for greater reliability. In these applications, the capacitors are worked at stresses comparable to d-c filter service, or about 1,000 volts per mil or less.

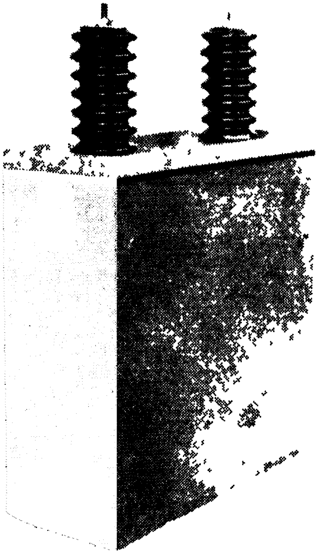


FIG. 47. One-quarter-microfarad, 100-kv, d-c surge-generator capacitor unit.

In energy-storage welding, the problems are much the same as in the other energy-storage applications except for the fact that the charging voltage is usually low, of the order of 3,000 volts, and the repetitive rate is fairly high, as, for example, 150 per minute. A bank of capacitors is charged by means of a rectifier and then discharged through the primary winding of a welding transformer, while the secondary of the transformer has its circuit completed through the weld. For each capacitor discharge a very high current of short duration flows through the weld. In this manner welds can be completed before oxidation takes place on metals such as aluminum. A typical capacitor for energy storage welding is shown in Fig. 49. About 20 such units are used in an average welder, giving an energy storage of 10,800 watt-sec. It has been customary to work capacitors of this type at 1,500 volts per mil when the discharge is nonoscillatory and does not reverse more than about 10 per cent. In some applications, the same capacitors are used at a reduced charging voltage. When the voltage completely reverses polarity, the voltage per mil is held down to 1,000 or 1,100, either by reducing the applied voltage or designing the unit with thicker dielectric.

CAPACITORS FOR SURGE PROTECTION OF ROTATING MACHINES

Rotating machines such as motors, a-c generators, and synchronous condensers are more difficult to insulate against incoming lightning surges than are transformers. When they are connected to overhead lines they are exposed to lightning and, therefore, should be protected

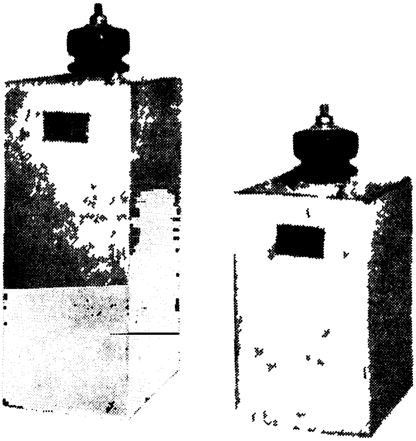


FIG. 48 High-voltage d-c capacitors for X-ray application

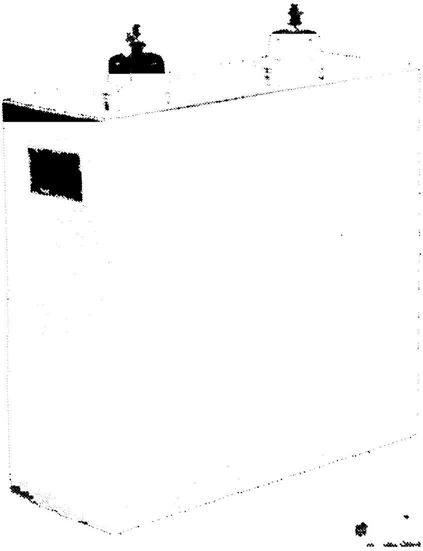


FIG 49 Three-thousand-volt, 120-μf, d-c, energy-storage welding capacitor

against lightning surges Lightning surges may build up voltage on the end turns of the inductive windings in these machines.

Protecting these machines against surges involves limiting the voltage on both the major insulation and the turn insulation in the windings.

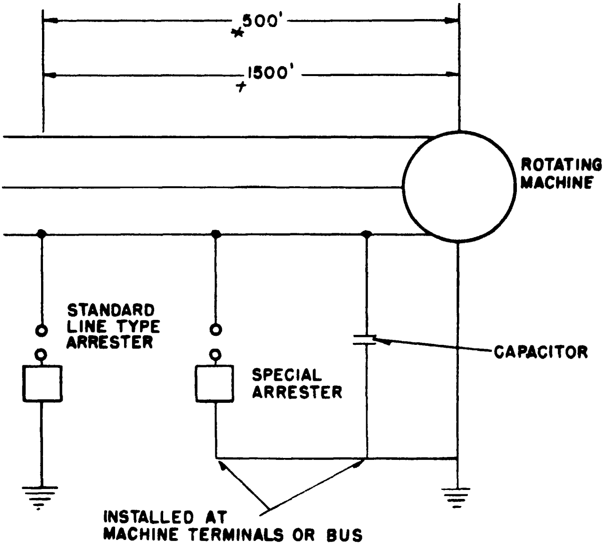

*500'
†1500'
ROTATING MACHINE
STANDARD LINE TYPE ARRESTER
SPECIAL ARRESTER
CAPACITOR
INSTALLED AT MACHINE TERMINALS OR BUS

Fig. 50. Typical diagram showing protective devices for a machine directly connected to an overhead line.

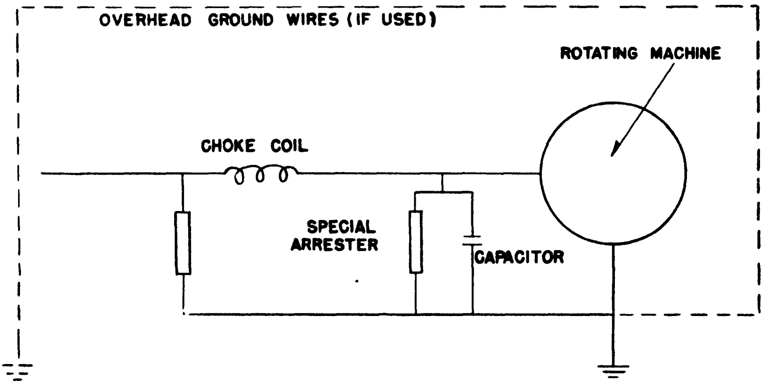


Fig. 51. Protection to rotating machines connected through choke coil to overhead lines.

This necessitates limiting both the magnitude and the steepness of the incoming surges.

It is necessary to limit the slope, or steepness, of the surge because the voltage applied to the turn insulation depends upon the steepness of the surge as well as the electrical length of the winding. In single turn windings, the turn insulation is usually the same as the insulation to ground, or major, insulation; but in multiturn windings, the turn insulation is usually less than the major insulation.

Lightning arresters are used to protect the major insulation. Capacitors are used to slope off the incoming wave and protect the turn insulation.

Figure 50 shows a typical arrangement where the surge impedance of the line is made use of. In this scheme of protection a lightning arrester is installed at the machine terminals to limit the magnitude of the voltage peak applied to the machine windings. The purpose of the capacitor is to slope off the voltage surge. The sloping is accomplished by means of a capacitor which must be charged through the surge impedance of the line. The rate of rise in voltage is also determined by the size of the capacitor. A value of 0.5 μf is commonly used.

Figure 51 shows a scheme of protection using a choke coil and capacitor in combination with an arrester. The magnitude of the incoming surge is limited by a lightning arrester, while a lumped inductance and capacitor are used to limit the slope of the surge. With this scheme the machine is protected against all surges in a very effective manner.

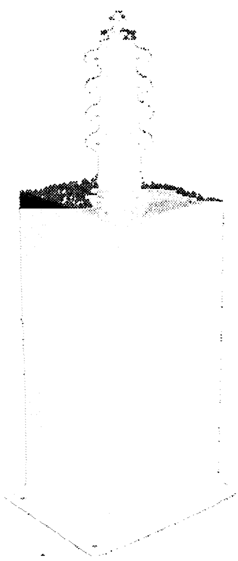


Fig. 52. One-quarter-microfarad capacitor for use on a 13,800-volt circuit for surge protection.

The arrester is applied on the line side of the choke in order to limit the voltage which determines the charging rate of the capacitor. The rate of rise of the capacitor voltage will depend upon the value of both inductance and capacitance used.

Capacitors used for this purpose are generally connected from line to ground and therefore the case is used as one terminal of the capacitor. Figure 52 shows a typical 0.25-μf capacitor unit for use on a 13,800-volt circuit. Two such units may be used together on each phase to give 0.5 μf capacitance. For lower voltages capacitors are often built with three elements in one case star-connected with the case to form the neutral and ground.

CHAPTER 4

APPLICATION OF SHUNT CAPACITORS TO INDUSTRIAL POWER CIRCUITS

The power factor of a circuit is the ratio of true power in watts to the apparent power as obtained by multiplying the current flowing to the load by the circuit voltage.

In a-c circuits the power factor is usually less than unity because current and voltage are not in phase. When the wave form is sinusoidal the power factor is equal to the cosine of the phase angle.

Figure 53*a* shows the conditions where the current and voltage are exactly in phase. The power in this case is equal to the product of voltage and current.

Figure 53*b* shows the condition where the current lags the voltage by 90 deg. The positive power is exactly offset by negative power with the result that there is no net, or true, power. Magnetic energy is stored up in the load during one half cycle and returned to the circuit in the other half cycle.

Figure 53*c* shows the condition where the current leads the voltage by 60 deg. The negative power is small and does not cancel the positive power, with the result that the true net power is substantial. The same is true if the current is lagging with respect to the voltage as shown in Fig. 53*d*.

The difference in Figs. 53*c* and 53*d* is in the cause of the negative power indicated. The negative power shown in Fig. 53*d* is due to magnetic energy in the load, such as would be the case with machines employing magnetic fields, as, for example, a motor. The negative power shown in Fig. 53*c* is due to electrostatic energy in the load, as would be the case if a capacitor were connected in parallel to a unity-power-factor load.

The power factor of a single-phase circuit may be obtained from wattmeter, voltmeter, and ammeter readings and has the relation

$$\frac{P}{E \times I} = \cos \theta$$

where P = watts.
E = voltage.
I = current.

The power factor of a three-phase circuit which has balanced loads is the same as the power factor of the individual phases. For unbalanced polyphase circuits, it is usually sufficiently accurate to assume the power factor to be that obtained by methods which give the average of the power factors of the separate phases.

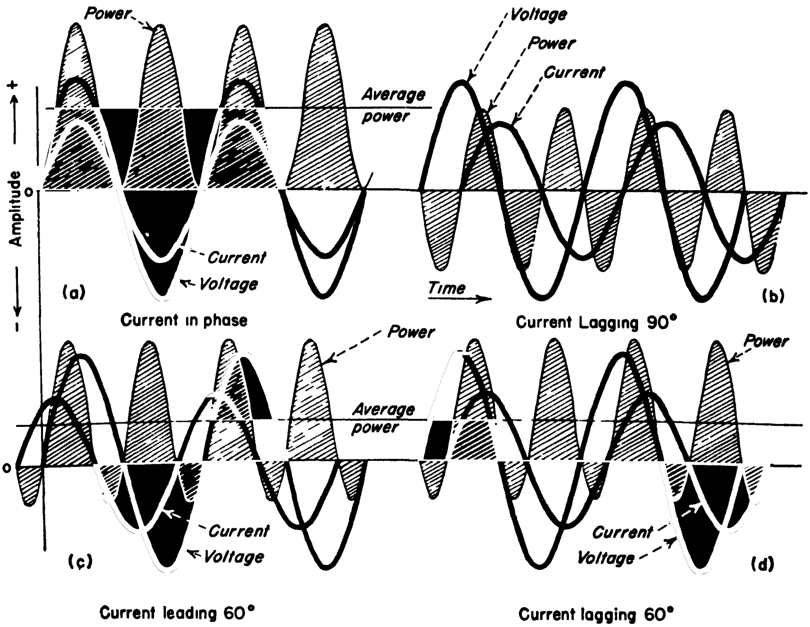


FIG. 53. Sine-wave illustration of leading and lagging power factor.

These relations may be stated another way as follows:

$$\text{Power factor} = \frac{\text{active power (kw)}}{\text{apparent power (kva)}}$$

$$\text{Reactive factor} = \frac{\text{reactive power (kvar)}}{\text{apparent power (kva)}}$$

$$\text{Apparent power} = \sqrt{\text{kw}^2 + \text{kvar}^2}$$

$$\text{Active power} = \sqrt{\text{kva}^2 - \text{kvar}^2}$$

$$\text{Reactive power} = \sqrt{\text{kva}^2 - \text{kw}^2}$$

When stated in terms of angles, we have

$$\begin{aligned} \text{Power factor} &= \cos\theta \\ \text{Reactive factor} &= \sin\theta \\ \text{Apparent power} &= \frac{\text{kw}}{\cos\theta} \\ \text{Active power} &= \text{kva} \times \cos\theta \\ \text{Reactive power} &= \text{kw} \times \tan\theta \end{aligned}$$

With long high-voltage transmission lines the charging current caused by the capacitance of the line may give rise to currents which are leading with respect to the voltage and the circuit power factor may be leading. This is not the case, however, with power circuits supplying industrial loads at relatively low voltages, because the charging current due to the capacitance of the circuit and the loads is negligible. The equipment connected to these circuits, however, is usually of a type containing magnetic fields such as motors, welders, and the like, with the result that the current is lagging with respect to the voltage and the power factor is usually lagging.

POWER FACTOR OF INDUSTRIAL LOADS

In d-c motors, the current flows in one direction only and the motor field remains continuously magnetized as long as the motor is connected to the line.

In an a-c induction motor the field is magnetized and demagnetized for each reversal of the current. This magnetizing and demagnetizing of the motor field accounts for most of the reactive component of this type of load.

Other loads in industrial plants may have low lagging power factor, however, such as welders and furnaces.

Induction motors generally constitute the predominating low-power-factor loads, first because there are so many of them and second because of the inherent design problems associated with induction motors. The motor draws an exciting current from the line to produce its field flux. This is similar to the exciting current drawn by a transformer except that instead of being about 5 per cent as in the case of a transformer, it is nearer 20 per cent of full-load current. This is due to the necessity of a large air gap in a motor. Slow-speed motors require more exciting current because of the larger number of poles. This exciting current is almost entirely reactive.

In addition to the exciting current, the effect of load causes more current to flow in the stator and rotor. This current flows through the leakage reactance of the motor causing additional lagging kvar (I^2X) varying as the square of the load current and amounting to 15 or 20 per cent of full load current. This kvar component is large or small depending on the leakage reactance of the motor, and the leakage reactance of a motor must be made high enough to keep the initial inrush current within reason and to permit "across-the-line" starting.

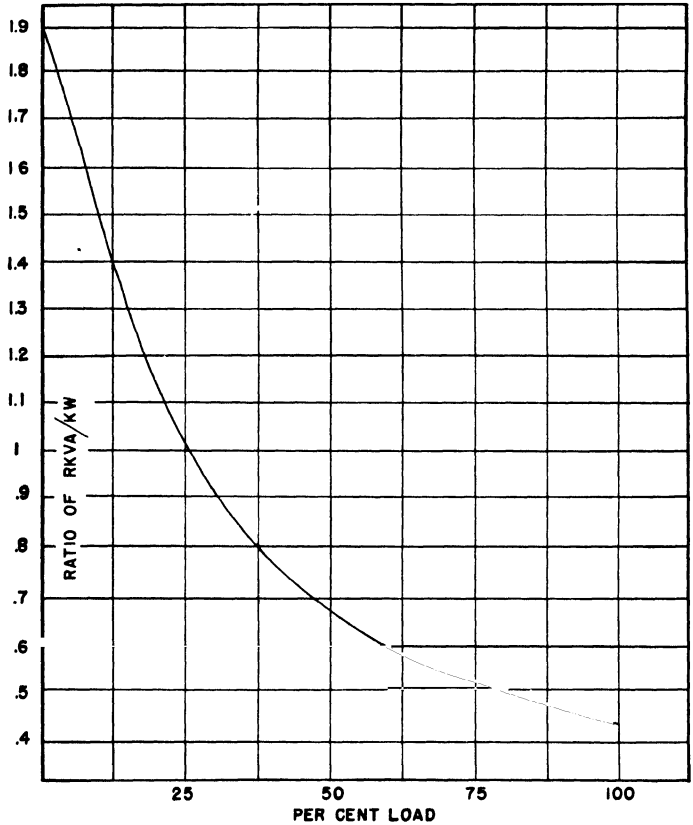


Fig. 54. Effect of load on motor power factor.

The total kvar, or kilovars, drawn by an induction motor consists of the sum of the exciting or magnetizing current and a component that varies as the square of the load. A typical motor varies from 20 per cent power factor at no load to 85 per cent at full load.

It is to be expected that motors in most industrial plants are generally operating at light load. Motors must be selected for the worst conditions that may prevail and quite often the starting requirements determine the size of the motors rather than the load conditions. The motor may therefore operate at 25, 50, or 75 per cent of its rated load. While the power factor of motors at full load is usually quite high, the power factor under the actual operating conditions is more likely to be 60 or 70 per cent. One motor as shown in Fig. 54 operating at 25 per cent load draws as much kvar from the line as kw.

Motor loads are not by any means entirely responsible for low power factor in industrial plants. Welders are nothing more than transformers with a highly reactive load on the secondary. The secondary is usually a short loop having a voltage which is low in relation to the secondary inductance. The high secondary current produces relatively high inductive drop, and this load viewed from the primary side appears as a 40 or 50 per cent power-factor load.

Induction furnaces of the type in which the molten metal forms a short-circuited loop around a magnetic circuit have low power factor for the same reason as the welders, namely that the secondary voltage is small in relation to the inductive drop in the secondary loop. The reactive drop and load voltage are quite comparable and the power factor is low.

In some plants, processes require large currents and extensive low-voltage circuits, resulting in poor power factor just as with the case of welders and induction furnaces. A typical example is a graphitizing furnace, which is usually 75 to 100 ft long and requires 35 to 40 volts and a current of 40,000 to 50,000 amp. The electrical circuit necessary to connect to each end of the 100-ft furnace has a certain irreducible amount of inductance even when steps are taken to minimize it as much as possible. While this inductance is numerically small, the inductive drop is equal or greater than the voltage required to overcome the resistance of the furnace. The resulting power factor is often as low as 40 per cent even though the load itself is generally looked upon as a resistance load having high power factor.

EFFECT OF POWER FACTOR ON VOLTAGE

In the utility's line from the source to the load there is a reactance drop due to the flow of this reactive or magnetizing current required by inductive loads. This reduces the voltage delivered to the power consumer.

The performance of motors is very much dependent on the voltage at the motor terminals. Reduced voltage reduces the starting torque and increases the full-load current. The speed is also affected to some extent. Figure 55 shows the effect on one type of motor.

The magnitude of this drop in voltage is illustrated by Table 8. This table is based upon a typical 4-kv feeder using 4/0 wire with a three-phase equivalent spacing of 33.6 in. and a fixed load of 1,000 kw.

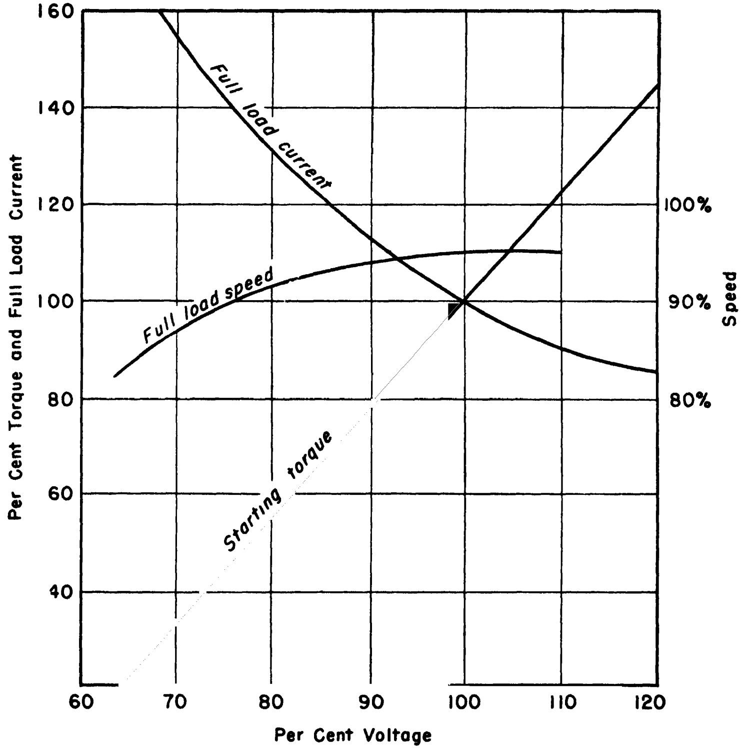


FIG 55 Effect of voltage on motor performance

The receiving voltage can be arrived at from the expression

$$E_r = E_s - I\,(R \cos\theta + X_L \sin\theta) + jI\,(X_L \cos\theta - R \sin\theta)$$

where E_s = sending voltage.
E_r = receiving voltage.

This can be simplified, however, without appreciable error by dropping the $+j$ term and calculating the voltage drop by adding the drop caused by the in-phase component of current multiplied by circuit resistance and the out-of-phase component of current multiplied by the circuit reactance.

$$E_r = E_s - (I \cos \theta) R + (I \sin \theta) X_L$$

Referring to Table 8, it will be noted that even at 99 per cent power factor the reactive component is already 14.2 per cent. At 70.7 per cent power factor the two are equal, and the voltage drop caused by the reactive component is nearly 4 per cent while the drop caused by the active component is less than half as much.

Supplying this reactive component from the generator burdens voltage regulators, overloads transformers and all equipment whose size is measured by total line current, and produces considerable additional losses in transformers and lines. The voltage is stepped up once and down at least three times before it reaches the load, giving ample opportunity for losses in these transformations.

TABLE 8

Load power factor	Per cent reactive component	Per cent active component	Per cent per mile drop due to active component	Per cent per mile drop due to reactive component	Per cent per mile total drop	Current, per cent
100	0	100	1.89	0	1.89	100
99	14.2	100	1.89	0.56	2.45	101
95	33	100	1.89	1.29	3.18	105
90	47.8	100	1.89	1.94	3.83	111
85	60.5	100	1.89	2.43	4.32	118
80	75	100	1.89	2.94	4.83	125
70.7	100	100	1.89	3.92	5.81	142
60	133	100	1.89	5.21	7.10	167
50	174	100	1.89	6.80	8.69	200

Based on 4-kv feeder, three-phase equivalent spacing of 33.6 in fixed load of 1,000 kw
Resistance per mile = 0.303
Reactance per mile = 0.629

The load that can be handled through lines, transformers, and regulators and the output of generators is measured largely in current rather than real power. The load that can be delivered over lines, particularly at 13 kv and below, is often determined by current-carrying capacity. Even when current-carrying capacity is not the limiting factor the power that can be transmitted is often determined by delivered voltage. If the load is of low power factor such as 50 per cent, the current flowing is quite large as indicated in Table 8 and the voltage drop is often quite troublesome. Even with a more common power factor of 70 per cent the voltage drop due to reactive current exceeds the drop due to the kw component by a factor of about 2.

The voltage-regulation curve for a transformer is also greatly affected by the power factor of the load as shown in Fig. 56.

It is obvious from the above that efficient use of lines and power-distribution equipment and the maintenance of satisfactory voltage levels at the receiving end are possible only when the lines and equipment are relieved of handling this lagging kvar required by the inductive or low-power-factor loads.

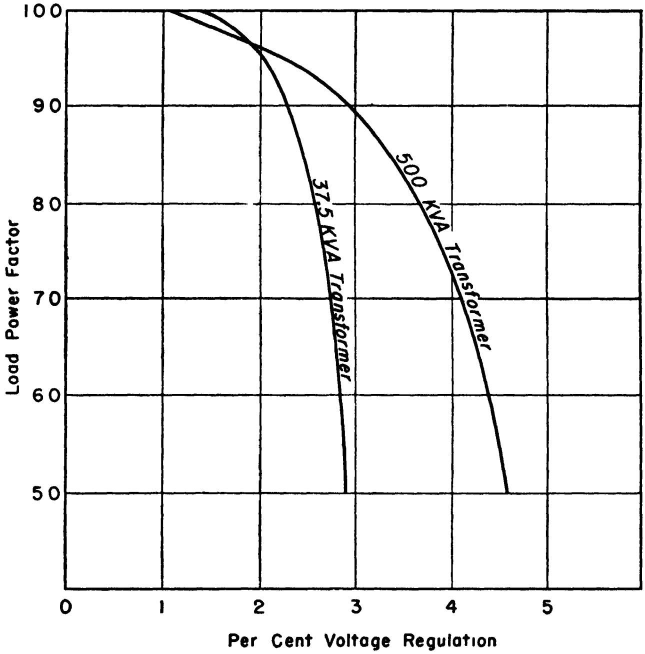


FIG. 56. Effect of load power factor on transformer regulation.

USE OF SHUNT CAPACITORS TO IMPROVE POWER FACTOR

A shunt capacitor offers an ideal means of supplying kvar to a load since it may be placed in convenient-size units or banks at the load or at load centers and the cost per kvar is not greatly affected by the size of the bank unless the total kvar of the bank is less than 45 for a three-phase bank. It is therefore possible to scatter the capacitors throughout an industrial plant as the load is scattered or concentrate the capacitor at load centers, depending on requirements. This ability to locate the capacitor near the load or distribute it at many points on the system is one of the outstanding advantages of capacitors.

The separation of kilovolt-amperes into two components, kilowatts and kilovars, or reactive kilovolt-amperes, is receiving an increasing amount of attention in the industry. Each of these components is being viewed as a distinct entity. A generator is considered as generating and feeding both kilowatts and kvar into the power system. A synchronous condenser or synchronous motor may absorb kilowatts from the system while feeding kvar into the system, when the excitation is so adjusted.

It naturally follows that a shunt capacitor may be looked upon as a device for supplying kvar to the system. If the capacitor is located near the load that demands the kvar component, the line and all equipment between this point and the source are relieved of supplying these kvar and when so relieved can supply more useful kilowatts which is the real purpose of this equipment.

POWER-FACTOR IMPROVEMENT FROM THE VIEWPOINT OF THE INDUSTRIAL PLANT

The benefits of capacitors from the standpoint of the industrial-power user are measured in two ways: first, in terms of saving on the power bill through rate structures that have been created by the utility to encourage high-power-factor loads. Raising the power factor of the entire plant load reduces the kva demand charge, and in most cases the actual energy charge. Secondly, the industrial power user may reduce kva burden on the plant-owned transformers, reduce the losses in the plant feeders, and maintain better voltage at the motor terminals.

When the only consideration is over-all plant power factor the application is quite simple. The kvar rating of capacitors needed to raise present power factor to any desired power factor can be determined by simple calculations.

The size of the capacitor that can be justified depends on the particular power rates and the manner in which credit is given for raising the power factor. These rates vary a great deal throughout the country but in general the saving returns the first cost of the capacitor in 1 to 3 years.

LOCATION OF THE CAPACITOR

If analysis of plant conditions indicates that advantages can be gained by relieving the user's transformer of kvar or by improving circuit voltage regulation, consideration should be given to placing the capacitors on the load side of the power transformers or even out on the feeders or directly on low-power-factor loads. Whatever savings result from these special locations of the capacitor add to the saving obtainable from the utility. In attempting to make these additional gains the cost of the capacitors may be increased for the same total capacitor kva due to the causes enumerated below:

1. Use of 230-volt capacitors instead of 2,400-volt or higher voltage capacitors.
2. Use of many small installations with additional switches and installation expense.

The investment in capacitors totaling the same kvar may actually be reduced by placing them out in the plant for the following reasons:

1. Lower cost switching equipment may be usable. When the capacitor is placed directly on the primary a larger breaker with high interrupting capacity may be required, whereas these fault currents may not be large out on the plant circuits due to current-limiting reactance of the circuit.
2. Automatic change in kvar may be provided by direct connecting of capacitors to loads, rather than by automatic switching of parts of the main bank by electrically operated breaker of high short-circuit rating.

Placing a substantial portion of the capacitor directly on the load may result in a greater installed kvar of capacitors due to diversity factor. Some of the capacitors may be idle when certain motors are not running.

The proper application of capacitors in industrial plants often involves an evaluation of all these factors and to this extent the selection of the capacitors cannot be arrived at by any simple rule.

Shunt capacitors may be connected directly to the terminals of motors and switched on and off with the motor, using the motor-control switches. In applying capacitors in this manner it is desirable to avoid the use of capacitors larger than are required to raise the no-load power factor of the motor to unity. The use of capacitors larger than this may cause self-excitation when the motor is disconnected from the line. If the capacitor current exceeds the no-load excitation current of the motor, the latter may act as a generator with undesirable results. This method of correcting motor power factor is desirable in that it provides a means of automatically varying the capacitor kva to suit changes in loads. It is undesirable because it does not take advantage of diversity factor, and results in a higher installation cost due to the large number of individual installations.

Shunt capacitors may be directly connected to welders and switched with the welder. This is desirable only on welders with which the duration of weld is quite long and the welder has an important effect on steady-state power factor of the plant load. On spot welders, where the duration of welding time is short and where the instantaneous kva demand is most important, it is better to use series capacitors.

In the first type of welder one is primarily interested in the steady-state power factor and the initial transient is not so important because its duration is short compared to the length of the weld.

In the second type, as, for example, where the duration of the weld is made up of one or two cycles on and a few cycles off, the transient becomes important relative to the weld duration; in an application of this kind one is interested in the instantaneous kva demand of the welder and means of reducing it. A shunt capacitor cannot be conveniently used to reduce the instantaneous demand because it also draws a large inrush current. It can, however, cut down the steady-state demand.

A series capacitor placed in series with the welder will reduce the instantaneous kva demand and the inrush may be reduced to a value corresponding to the kilowatt demand. This is covered in a later chapter.

Other types of loads of a steady type may usually be provided with shunt capacitors, such as 60-cycle induction furnaces, or separate plant circuits may be treated as single loads and individually provided with capacitors.

The choice and location of capacitors in industrial plants is governed by the load pattern, distribution of loads, shifting of load centers, and many other factors which vary in each plant. The reason for improving power factor may be one of power rates alone or may involve relieving of transformer or circuit overloads, maintainance of voltage at the motor terminals, or a combination of several reasons.

It is therefore desirable to set down all the reasons for improving power factor and enumerate the possible gains before attempting to decide where to place the capacitors or what types of capacitors to install.

POWER RATES

The investment in a generating plant and distribution system is relatively high compared to the annual revenue and is based on maximum loads, while the revenue is determined by the average loads.

The problem of apportioning the cost of delivered energy among the various consumers of several classes is complicated. It is not possible to apply a general rate schedule which would be equitable for the wide range of service required by the various consumers. Several rates are usually used to cover the various classifications.

Electric rates are based on classifications, diversity factors, load power factor, demand power factor, and, sometimes, monthly power factor, as well as the cost of producing the energy. When power factor is taken into account, this in a measure compensates for the variations in cost of delivery of the product to the users' premises.

When the power factor is low it is difficult for the utility to render good voltage regulation. The losses in the system are lower, and the investment in system equipment is larger. Capital charges and maintainence expense in all parts of the system such as generators, lines, transformers, substations, and regulators are increased.

It is for the reasons above that the so-called "power-factor clauses" came into use some twenty or thirty years ago.

The purpose of the power-factor clause is to distribute the charges for delivering the power in accordance with the cost of delivery.

Many power-factor clauses are based on the maintenance by the consumer of an average power factor of 85 per cent. The kwhr consumed are multiplied by a factor, which varies with the power factor, to arrive at the kwhr for billing purposes.

Where a demand charge is used the metered demand is sometimes multiplied by this same factor to obtain the billing demand. Where the demand is measured in kva rather than kilowatts, the matter of power factor is automatically taken into account, since poor power-factor loads result in high kva demand.

One type of rate determines the energy charge by setting up several blocks of power, with each block at a reduced rate over the preceding one. The size of the block is made equal to the kva demand multiplied by some number. The size of the block is therefore governed by the kva demand, and the larger the kva demand, the more power is billed at the higher rates.

There are a wide variety of ways in which power factor is taken into account but the purpose is always the same, namely, to penalize for low power factor and to establish credit for high power factor. Another object, of course, is to reimburse the consumer for investment in equipment added to supply the kvar to his load and thus relieve the lines of this added burden.

CAPACITOR KVA REQUIRED

To raise the power factor of a given load from one power factor to a higher power factor involves a very simple calculation. One has only to calculate the present kvar and the kvar corresponding to the new desired power factor. The difference is the kvar that must be supplied by the capacitor. This will be clear from the following example.

Present load = 100 kw.

Present power factor = 45 per cent (desired 85 per cent).

Present kva $= \dfrac{100}{0.45} = 222.$

Present kvar $= \sqrt{222^2 - 100^2} = 198.$

Kva at desired power factor $= \dfrac{100}{0.85} = 117.8.$

Reactive kva at desired power factor $= \sqrt{117.8^2 - 100^2} = 61.6.$

Capacitor kva required $= 198 - 61.6 = 136.4.$

If the power factor is low, the demand kva will be high. If the rates include a kva demand charge, this may be reduced by raising the power factor during the demand peak. With a demand of 1,200 kw and 75 per cent power factor, the kva demand is

$$\frac{1{,}200}{0.75} = 1{,}600 \text{ kva}$$

If the power factor is raised to 95 per cent the kva demand is

$$\frac{1{,}200}{0.95} = 1{,}260 \text{ kva}$$

The size of the capacitor required to accomplish this is determined from the kvar at the two values of power factor as follows:

Kvar at 75 per cent power factor $= \sqrt{1{,}600^2 - 1{,}200^2} = 1{,}060.$

Kvar at 95 per cent power factor $= \sqrt{1{,}260^2 - 1{,}200^2} = 387.$

Kva rating of capacitor $= 1{,}060 - 387 = 673.$

The reduction in the kva demand from 1,600 to 1,260 may either result in simply a reduced kva demand charge or it may actually reduce the energy charge, depending on the rate structure. Some rates involve several energy charges for successive blocks of power, the size of the blocks depending on the kva demand. For example:

Size of block = 70 × kva demand.
First block at 5 cents per kwhr.
Second block at 1¼ cents per kwhr.
Third block at 1 cent per kwhr.
Additional blocks at ¾ cent per kwhr.

It is plain to see that in this case the energy charge will be reduced by reduction in kva demand, because if the blocks are smaller, the consumer will reach the low rate on a larger proportion of the energy used.

Sometimes a check is made as to the average power factor under day-load conditions, and the billing thereafter is based on this until some future check is made. The energy charge, or the net billing, is adjusted up or down according to this power factor. In such cases it is necessary to determine how this check is to be made and under what conditions, and to install capacitors to raise the power factor as high as warranted by the expected savings. After the capacitor is installed, the utility will be asked to check the power factor again and set up the new rate accordingly. Such a capacitor is usually made proportional to day-load requirements. In the case above, the day load averaged 960 kw at 67 per cent power factor. Assuming this is to be brought up to 95 per cent power factor, a 720-kva capacitor is required as follows:

$$\frac{960\text{ kw}}{67\text{ per cent}} = 1{,}430\text{ kva}$$

$$\text{Kvar at 67 per cent power factor} = \sqrt{1{,}430^2 - 960^2} = 1{,}035.$$

$$\text{Kva at 95 per cent power factor} = \frac{960}{0.95} = 1{,}010.$$

$$\text{Kvar at 95 per cent power factor} = \sqrt{1{,}010^2 - 960^2} = 315.$$

$$\text{Capacitor kvar required} = 1{,}035 - 315 = 720.$$

A type of rate quite commonly used is one which takes into account monthly power factor based on the integrated kwhr and kvar-hr. This type of rate may be encountered under various conditions as follows:

1. Where the kvar-hr meter is not equipped with a ratchet.
2. Where the kvar-hr meter is equipped with a ratchet and load is reasonably uniform.
3. Where the kvar-hr meter is equipped with a ratchet but the load varies greatly during the month.

When condition 1 prevails it follows that the capacitor may be left connected to the line continuously and the total kvar multiplied by the number of hours in the month. If there is no ratchet on the meter, full credit results from the use of the capacitor regardless of whether the power factor is leading at times.

This is further explained by the following example:

Kwhr for the month = 314,550.
Kvar-hr for the month = 337,146.
Kilowatt demand during month = 1,200.

Demand charge = \$1 per billing kva demand.

Billing kva demand = kw demand $\times \sqrt{1 + \left(\frac{\text{kvar-hr}}{\text{kwhr}}\right)^2}$.

Energy charge:

1. First block at 2 cents per kwhr.
2. Second block at 1 cent per kwhr.
3. Third block at ½ cent per kwhr.

Block determination:

1. First block = 1,000 kwhr plus 40 × the billing kva demand.
2. Second block = 40 × billing kva demand.
3. Third block = 40 × billing kva demand.

Analyzing the above, it will be noted that for each unit reduction in billing kva demand \$1 will be saved. The kwhr size of the first block will be reduced by 40, saving 80 cents, and the kwhr size of the second block will be reduced by 40, saving 40 cents. It will increase the kwhr in the third block by 80 kwhr, adding 40 cents. The total saving, therefore, for each unit reduction in billing kva demand is \$1.00 + 0.80 + 0.40 − 0.40 = \$1.80.

In this case, let us assume that we want to reduce the billing kva demand by 495 by adding capacitors. The saving in this case will be 495 × \$1.80, or \$891 per month. We must now determine the kvar-hr to be supplied by the capacitor and the required size of the capacitor.

Present billing kva demand $= 1{,}200 \times \sqrt{1 + \left(\frac{337{,}146}{314{,}550}\right)^2} = 1{,}758.96.$

New billing kva demand = 1,759 − 495 = 1,264.

Solving for new kvar-hr, we find

$$1{,}200 \times \sqrt{1 + \left(\frac{\text{kvar-hr}}{314{,}550}\right)^2} = 1{,}264$$

$$1 + \left(\frac{\text{kvar-hr}}{314{,}550}\right)^2 = 1.111$$

$$\frac{\text{Kvar-hr}}{314{,}550} = 0.333$$

$$\text{Kvar-hr} = 104{,}700$$

Therefore, to reduce the billing kva demand by 495 it will be necessary to reduce the monthly kvar-hr to 104,700 or to offset by capacitors 337,146 − 104,700, or 232,446, kvar-hr.

The capacitor rating needed to make this reduction is

$$232{,}446/730 \text{ (hr per month)} = 319 \text{ kva}$$

Regardless of the minimum or maximum load a 319-kva capacitor will offset the 232,446 kvar-hr required by the load. During heavy loads the power factor will be lagging and the kvar-hr meter will operate normally. During light loads the power factor may be leading in some cases and the kvar-hr meter will run backwards, with the net reduction in monthly kvar-hr by 232,446.

When condition 2 prevails the kvar-hr meter cannot run backwards. The capacitor must be large enough to build up accumulated kvar-hr only while the power factor is not leading.

Taking the same example, where the capacitor must reduce the total kvar-hr by 232,446 in the month, we must first consider the minimum load on the plant and the power factor at this time. Let us assume that we find the minimum load is 400 kw with a power factor of 76 per cent.

$$\begin{aligned} \text{Kw} &= 400 \\ \text{Kva} &= \frac{400}{76} = 526 \\ \text{Kvar} &= \sqrt{526^2 - 400^2} = 341 \end{aligned}$$

We now see that even for the minimum load it takes a 341-kva capacitor to correct the power factor to unity. Therefore, a 319-kva capacitor will not produce leading power factor at any time during the month, and we will get the full benefit of 319 × 730 or 232,446 kvar-hr from the capacitor even though the meter is provided with a ratchet.

When condition 3 prevails, that is, where a ratcheted kvar-hr meter is used and where the load fluctuates a great deal and drops to low values at times during the month, it is necessary to analyze the load pattern carefully if one is to avoid installing a capacitor larger than needed. We can see from the previous example that if the load drops at times much below 400 kw and 319 kva, the capacitor will not be 100 per cent effective throughout the month, which simply means that we must use a larger capacitor. The question immediately arises as to just how much larger it has to be.

Let us assume that in this case we must supply the same total kvar-hr by means of a capacitor, viz., 232,446 kvar-hr.

We must make a study of the plant operating schedule and develop the load pattern over a monthly period. This can be conveniently done by considering the load as having four levels, as follows:

1. Week end (lowest).
2. Night (next lowest).

3. Evening (next lowest).
4. Day load (highest).

An examination of the plant working conditions will readily provide a basis for estimating these load levels and the power factors. The following example will illustrate.

Level	Hr per month	Kw	Power factor, per cent	Kvar
Week ends..........	240	64	50	111
Nights	168	260	76	222
Evenings	168	640	70	650
Day loads.	154	960	67	1,065

From the above we can calculate the largest size of capacitor which can be used without producing leading power factor during any of the four periods. For example a 111-kva capacitor will be 100 per cent effective throughout the entire month because it will not raise the week-end load to leading, and the week-end load is minimum for the month.

$$111 \times 730 \text{ hr per month} = 81{,}030 \text{ kvar-hr}$$

A 222-kva capacitor will raise the night load to unity power factor. This capacitor cannot produce leading except for the period representing the week end, or 240 hr.

$$730 - 240 = 490 \text{ hr}$$

We already have taken credit for 111 kva of capacitor so we now take credit for 222 − 111, or another 111 kva, which is effective for 490 hr.

$$111 \times 490 \text{ hr per month} = 53{,}390 \text{ kvar-hr}$$

The two sizes of capacitors arrived at above will give a total of 81,030 + 53,390, or 134,420 kvar-hr. We need 232,446. We therefore require 98,026 kvar-hr additional.

We find that the period aside from nights and week ends is 322 hr per month, and the lowest level to which the load falls during this period is that represented by the evening load of 640 kw at 70 per cent power factor. A 650-kva capacitor can be used during this period without producing a leading power factor. Since we have already assumed 222-kva of connected capacitor, we will consider only the addition, which is 650 − 222, or 428 kva of capacitors.

A 428-kva capacitor operating 322 hr per month gives a kvar-hr value of 137,816, but we need only 98,026, so we divide 98,026 by 322 and find that 301 kva is sufficient.

The capacitor required in this case is, therefore, 111 + 111 + 301, or 523 kva.

It is, of course, not necessary to switch off the 301-kva capacitor during week ends and nights or the 111 and the 301 during week ends unless one encounters too much rise in voltage. We simply connect 523 kva 24 hr per day and we are sure that with the load pattern described the effective kvar-hr will be 232,446. Actually the 523-kva capacitor will accumulate 381,790 kvar-hr; but during 149,344 kvar-hr the power factor is leading and due to the ratchets this is not effective in reducing the billing kva demand.

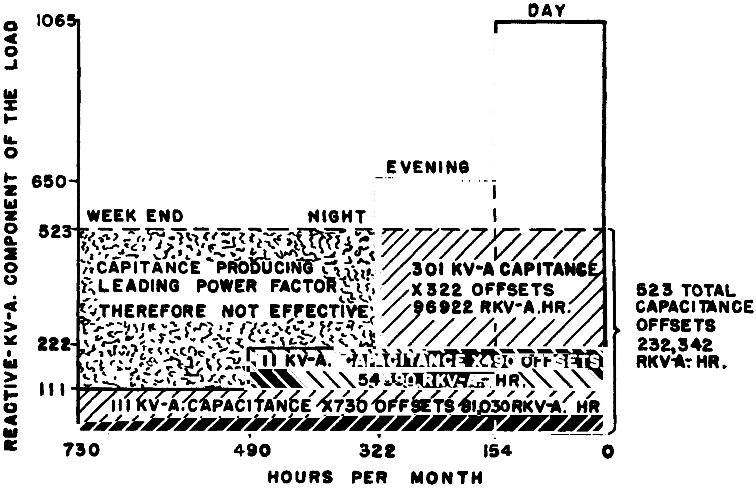


FIG. 57. Analysis of plant loads with respect to capacitor requirements.

The condition just discussed is graphically illustrated by Fig. 57.

NEED FOR REDUCING CAPACITOR KVA DURING LIGHT LOADS

Usually the only reason for varying the capacitor kva connected to an industrial-plant circuit is to avoid overvoltage at light loads. In large plants there may be sufficient need for switching the capacitor on and off in steps to match changes in load conditions. These will be discussed later under automatic control of kva.

Where one is interested primarily in the voltage boost a given capacitor will produce, the following procedure will be convenient to use. The calculations are based on a 550-kva capacitor.

1. *Calculation of rise through transformer:*

$$\text{Per cent rise through transformer} = \frac{\text{Ckva}}{\text{Tkva}} \times \text{transformer per cent reactance}$$

where Ckva = capacitor kva for total bank.
Tkva = transformer kva for total bank.

In this example we have 2,000-kva transformer bank, 5 per cent reactance, and 550-kva capacitor.

$$\frac{550}{2{,}000} \times 5 \text{ per cent} = 1.38 \text{ per cent rise in voltage through transformer}$$

2. *Calculation of rise in power feeder:*

$$\text{Per cent rise in voltage} = \frac{\text{Ckva} \times \text{ft} \times F}{1{,}000{,}000}$$

where Ckva = total kva of capacitor bank.
ft = length in ft of circuit under consideration.
F = factor, shown in tables below.

The factors (F) given in the table below are convenient and sufficiently accurate for estimating the voltage rise in most cases.

TABLE 9. FACTOR F FOR THREE-PHASE PRIMARY OPEN-WIRE FEEDERS

Feeder Voltage	F
2,400	2.24
4,160	0.75
4,800	0.56
7,200	0.25

NOTE: The above values can be used directly for two-phase four-wire and two-phase three-wire feeders. The above values should be doubled for single-phase feeders.

Assuming the feeder supplying this plant is one mile long and the circuit is 4,160 volts, three-phase open line,

$$\text{Per cent voltage rise in line} = \frac{550 \times 5{,}280 \times 0.75}{1{,}000{,}000} = 2.18 \text{ per cent}$$

If the capacitor is connected to the 460-volt side of the step-down transformers the total rise in voltage will, therefore, be 1.38 + 2.18, or 3.56 per cent.

If the capacitor is located at one point out in the plant on the 460-volt secondary circuit, there will be an additional rise, which will be quite important if the plant is wired with open wire. Usually cables or conduits are used.

3. *Calculation of rise in secondary circuits:* Assume that the 550-kva

capacitor is located at one point 600 ft from the transformer, on a 460-volt three-phase circuit of conduit or three-conductor cable, 500,000 cir mils.

Table 10 gives the factor F, similar to Table 9, for secondary feeders.

TABLE 10. FACTOR F FOR THREE-PHASE FEEDERS

Feeder voltage	Three-conductor cable			Open wire, 6-in. centers		
	No. 2	4/0	500,000 cir mils	No. 2	4/0	500,000 cir mils
230	56.4	47.2	45.6	184	157	138
460	14.1	11.8	11.4	46.1	39.2	34.4
575	9.1	7.6	7.3	29.6	25.2	22.1

NOTE: The above values can be used directly for two-phase four-wire feeders. The above values should be doubled for single-phase feeders.

$$\frac{550 \times 600 \text{ ft} \times 11.4}{1{,}000{,}000} = 3.75$$

The total rise at the capacitor will, therefore, be 1.38 + 2.18 + 3.75, or 7.31 per cent.

If the capacitor is split up into several separate banks and located on several secondary feeders, the rise will be less, as shown in the following example, assuming 4/0 three-conductor cables are used.

Department *A*:	110 kva, 600-ft feeder.
Department *B*:	110 kva, 200-ft feeder.
Department *C*:	330 kva, 300-ft feeder.
Total	550 kva

$$A = \frac{110 \times 600 \times 11.8}{1{,}000{,}000} = 0.78 \text{ per cent}$$

$$B = \frac{110 \times 200 \times 11.8}{1{,}000{,}000} = 0.26 \text{ per cent}$$

$$C = \frac{330 \times 300 \times 11.8}{1{,}000{,}000} = 1.17 \text{ per cent}$$

The rise will then be

In *A*: 1.38 + 2.18 + 0.78 = 4.34 per cent.
In *B*: 1.38 + 2.18 + 0.26 = 3.82 per cent.
In *C*: 1.38 + 2.18 + 1.17 = 4.73 per cent.

The rises of 1.38 per cent in the transformer and 2.18 per cent in the power lines are fixed in all three cases due to the assumption that all three capacitors are on.

This brings out the fact that when the total kva is broken up into several banks located on different plant feeders, there is less rise at light loads than if concentrated in one place. Also, that a group capacitor may be left on during light load with less rise when it is located at the service bank of transformers; and that open wiring in the plant will result in considerably more rise than when the plant circuits are in cable or conduit.

DETERMINATION OF THE MAXIMUM SIZE OF CAPACITORS DIRECTLY CONNECTED TO MOTORS

If the capacitor on a given motor is made too large, trouble may be encountered from the voltage generated when the motor is disconnected from the line. With this condition the motor acts as a self-excited induction generator and may generate voltages of sufficient magnitude to damage the insulation of the motor, or capacitor, or both. Also, if the motor switch is closed while the motor is operating as a generator, it is possible that high transient torque will be produced which will damage the motor shaft or coupling.

An induction motor may operate as an induction generator if its magnetizing kva is supplied by a capacitor. Figure 58 shows the magnetizing current characteristic of a typical motor operating at rated speed. Also shown are the volt-ampere characteristics of two typical capacitors, C I and C II. The voltage of self-excitation for a given capacitor and motor is given by the intersection of the capacitor and magnetizing characteristics. If the capacitor characteristic is above the motor characteristic, the capacitor kva is less than motor magnetizing requirements and no voltage will be generated. C I is such a capacitor and is approximately adequate to correct the no-load power factor to unity. Capacitor C II is approximately adequate to correct the full-load power factor of the motor to unity. With capacitor C II the self-excitation voltage is 150 per cent of the rated voltage of the machine. This value will vary widely for different motors and may be considerably higher for some.

This graphical determination of the voltage of self-excitation assumes that the motor will remain at or near rated speed for a sufficient time after the motor switch is opened for the generated voltage to build up to full magnitude. The rate at which the voltage builds up is extremely rapid in most motor applications, so that the maximum voltage is very close to the value determined in this way. However, a motor usually slows down rapidly after the switch is opened and the generated voltage collapses in a few seconds. In some cases, with high inertia loads, the voltage is sustained for several minutes.

Voltages generated by induction motors operating free of the line rarely reach sufficient magnitude to puncture the insulation; however, the continued application of voltages greater than 110 per cent of the rated voltage may materially reduce the life of the insulation.

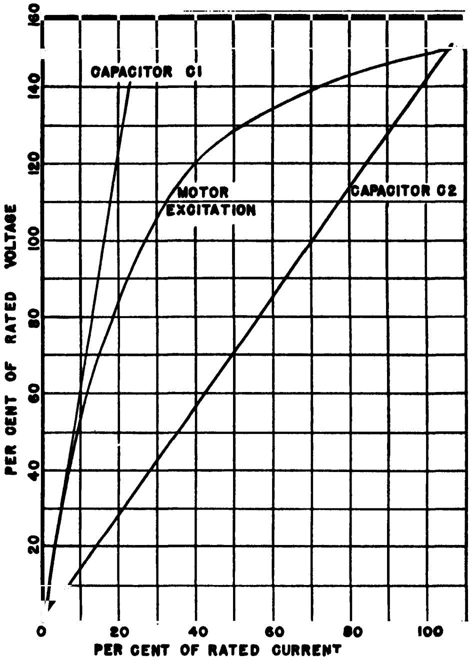


FIG. 58. Magnetizing current characteristic of a typical motor operating at rated speed.

Generated voltages may be dangerous even if they do not exceed the rated voltage. If a motor is operating as a generator and is connected to the line at a time when the generated voltage is out of phase with the line voltage, a high transient torque will be produced. If there is no load connected to the shaft, this torque merely results in a momentary acceleration or deceleration of the motor. If, however, the motor is loaded and the load inertia is high compared to that of the rotor, then most of the torque will be transmitted by the shaft and may do damage to the shaft and couplings.

Table 11 is a listing of the maximum capacitor ratings which can be used with various motors so that substantially no self-excitation voltage will be produced. If the size of capacitor does not exceed the value given for the motor in question, no trouble is to be expected in the application, either from overvoltage or transient torque. The value of capacity shown will correct the power factor of most motors to above 95 per cent, which is sufficient for most applications. The capacitor ratings given do not necessarily correspond to standard capacitor ratings and the next lower standard rating should be used.

TABLE 11. MAXIMUM CAPACITOR KVAR RECOMMENDED FOR DIRECT CONNECTION TO OPEN-TYPE THREE-PHASE 60-CYCLE INDUCTION MOTORS

Rating, hp	Two-pole, 3,600 rpm		Four-pole, 1,800 rpm		Six-pole, 1,200 rpm		Eight-pole, 900 rpm		Ten-pole, 720 rpm		Twelve-pole, 600 rpm	
	Rating, kvar	Current, per cent	Rating, kvar	Current, per cent	Rating, kvar	Current, per cent	Rating, kvar	Current, per cent	Rating, kvar	Current, per cent	Rating, kvar	Current, per cent
10	2.5	9	3.0	11	3.5	12	4.5	17	5.0	23	7.0	28
15	3.5	9	3.0	11	4.5	11	6.5	16	7.5	21	9.0	26
20	5.0	9	4.0	10	6.0	11	7.5	15	8.5	20	11.5	24
25	6.0	9	5.0	10	6.5	10	8.5	14	10.0	19	14.0	22
30	7.0	9	7.0	9	8.5	10	10.0	13	12.5	18	15.5	21
40	8.5	9	8.5	9	10.0	10	12.5	12	15.0	16	18.5	19
50	11.0	9	11.0	9	12.5	9	15.0	12	18.0	15	23.0	17
60	13.0	9	13.0	8	15.0	9	18.0	11	22.0	14	26.0	16
75	17.0	9	17.0	8	18.0	8	22.0	11	27.5	13	33.0	15
100	21.5	9	22.0	8	25.0	8	29.0	10	33.0	12	38.0	14
125	25.0	9	26.0	8	29.0	8	33.0	9	40.0	11	45.0	13
150	32.5	9	32.5	8	33.0	8	36.0	9	45.0	11	52.5	13
200	40.0	9	40.0	8	42.5	8	45.0	9	55.0	10	65.0	12

In some cases it may be desirable to use a capacitor larger than that shown in the table. In these cases the voltage generated when the motor switch is opened should be measured with a voltmeter. If this voltage is greater than 110 per cent of the rated voltage, the capacity must be reduced or separate capacitor-switching equipment must be installed so that the capacitor can be disconnected from the motor before or at the same time the motor switch is opened.

If the generated voltage does not exceed 110 per cent but does exceed

55 per cent of rated voltage, it is still necessary to ascertain that there will be no dangerous torque produced in the event the motor switch is reclosed while the motor is operating as a generator. The maximum torque which may be produced with various values of generated voltage

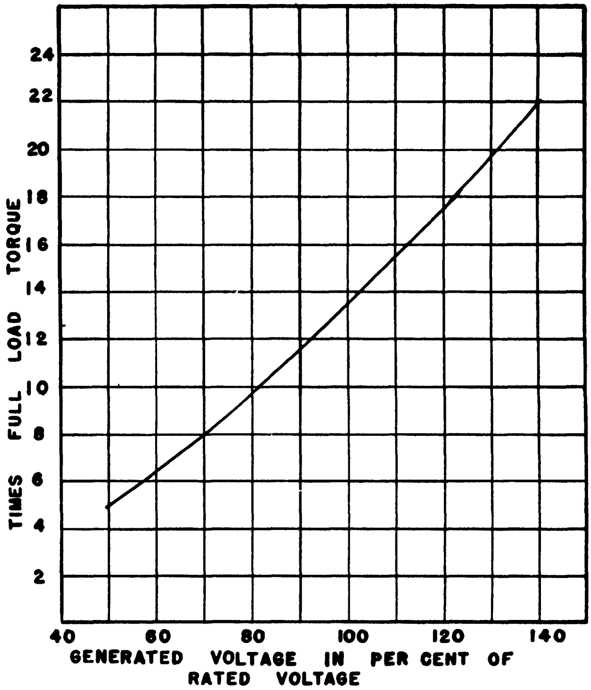


FIG. 59. Effect of reenergizing a motor and capacitor on motor torque.

is given by Fig. 59. The percentage of this torque which will be transmitted by the shaft may be determined from the following expression:

$$\text{Shaft torque} = \frac{J_L}{J_L + J_M} T_M$$

where J_L = rotational inertia of the load.
J_M = rotational inertia of the motor.
T_M = maximum torque determined from Fig. 59.

Most motor and shaft couplings are designed to stand an impact loading of approximately six times the rated torque. If the shaft torque exceeds this value, there is a possibility of damage.

When capacitors are connected to motor terminals, the current flowing in the line is reduced. If the capacitors are connected on the motor side of the overload protective device, this device will no longer give adequate protection if it has been selected for the uncorrected full load current. The relay or circuit breaker should be adjusted to operate at a lower current consistent with the reduced line current.

Bibliography

BARKLE, J. E.: Safe Capacitor Selection for Power Factor Improvement, *Power*, April, 1943.

CUTTINO, W. H.: Capacitors Reduce Losses and Raise Voltage, *Southern Power & Ind.*, October, 1941.

CUTTINO, W. H.: Plant Power Factor Reduced with Shunt Capacitors, *Eng. Mining J.*, vol. 147, no. 5.

CUTTINO, W. H.: Shunt Capacitors Reduce Costs and Increase Power Capacity, *Buildings and Building Management*, April, 1946.

MARBURY, R. E.: Capacitors May Be the Answer, *Southern Power & Ind.*, February, 1941.

MARBURY, R. E.: Power Factor Correction Releases Plant Capacity, *Electrical South*, March, 1942.

MARBURY, R. E.: When You Install Capacitors, *Factory Management and Maintenance*, September, 1940.

OWENS, J. B.: Use the Right Capacitor with Induction Motors, *Factory Management and Maintenance*, May, 1945.

Power Factor Bottlenecks, *Elec. Contracting*, February, 1944.

WATTS, T. H.: Short Cuts in Figuring Power Bills, *Elec. J.*, April, 1932.

CHAPTER 5

APPLICATION OF SHUNT CAPACITORS TO UTILITY SYSTEMS

Capacitors for power-factor correction first made their appearance about 1914. By 1928 capacitors handling some 260,000 kva were installed. By January, 1939, this had risen to approximately 1,400,000 kva. Up to about 1936 most installations of capacitors were made in industrial-plant circuits. The capacitors were installed by the power consumer to take advantage of the reduction in power billing.

INTRODUCTION OF OUTDOOR-TYPE CAPACITORS

The general practice of installing capacitors on the power lines started with the introduction of outdoor-type capacitor units suitable for mounting on the cross-arms of distribution-line poles. Later these outdoor units also were grouped into large substation banks. The practice of applying capacitors on the utility circuits was extended during the Second World War as a means of substantially increasing the power that could be handled over existing lines. By January, 1943, the total of installed capacitors was more than 5,000,000 kva and new installations were being added at an ever increasing rate.

NEW DEVELOPMENTS BROUGHT GENERAL USE OF CAPACITORS

Some of the reasons for this sudden interest on the part of the utilities are the following:

1. Reductions in price as a result of continuous advancements in the art had reached a point where the economic gains were very attractive.
2. The weight and volume of capacitors had been reduced to less than 20 per cent of what they were in 1924.
3. Improvements in design and control of materials and manufacturing processes had reduced maintenance to a very low cost.
4. A better understanding of system benefits was developing generally.

During the Second World War there were still further advantages, as follows:

1. Kilovars could be supplied with a minimum of critical material.
2. Manufacturing facilities could be more readily expanded for capacitors than for other means of supplying or handling kvar, such as synchronous condensers, new lines, transformers, etc.

The industrial plant or other power user is generally interested in capacitors from the standpoint of rate structures, which are set up based on average conditions rather than specific cases.

To the utility engineer the use of capacitors is purely a matter of economics. The main benefits that result from the use of capacitors are

1. Reduction in losses associated with the delivery of electrical power to the point of use.
2. Reduction in the investment required in equipment for delivering electrical power to the point of use, which may be broken down into
   - *a.* Reduction in current for the same kilowatt load.
   - *b.* Reduction in the kva rating of equipment required to handle the same kilowatt load.
   - *c.* Reduction in voltage drop for a given kilowatt load.
   - *d.* Control of delivered voltage if the capacitor kva is varied.

All these benefits go hand in hand but for the purpose of discussion they will be considered separately.

BENEFITS OF CAPACITORS TO UTILITIES

The reduction in losses may be stated either in terms of fuel saved or in terms of reduced burden on the generators and equipment. As the system is operated closer and closer to capacity, losses must be evaluated in both the total equipment capacity released and fuel saved. Reductions in system current not only reduce losses in lines, transformers, and regulators but release generator capacity necessary to supply these losses. Also supplying kvar to the load by means other than the generators not only releases generator capacity but eliminates the losses originally in the generator, when these kvar are supplied by the generator. The reduction in feeder copper losses may be approximated by the formula:

$$L = \frac{\text{Ckva} \times R\ (2\ \text{kva} \sin\theta - \text{Ckva})}{1{,}000 \times \text{kv}^2}$$

where L = reduction in three-phase feeder copper losses, kw.
R = resistance in ohms from substation to load center, the latter being the point at which all the load is assumed to be concentrated.
Ckva = three-phase capacitor kva.
kva = three-phase load kva (average for typical 24-hr period).
θ = power-factor angle of load, corresponding to average value of load.

$$\text{Reduction in losses per year} = 8{,}760 \times L \text{ kwhr}$$

The effect of capacitors in reducing the system losses is further shown by Table 12. This shows the reductions in energy loss which occur when the power factor of the load is increased.

TABLE 12. REDUCTION OF SYSTEM LOSS BY CAPACITOR

Power factor of load		Reduction in losses, per cent
Initial	Final	
70	0.70	0
	0.80	23
	0.90	40
	1.00	51
75	0.80	12 5
	0.90	31
	1.00	43
85	0.90	10
	0.95	25
	1.00	32.5
90	0.95	10
	1.00	18

NOTE: The reduction in energy losses is the per cent reduction from the losses which existed at the initial power factor values.

KILOWATT GAINS IN LINE CAPACITY WHERE CURRENT IS THE LIMITING FACTOR

The reduction in current for a given load may be restated in terms of increasing load limits where current-carrying capacity is the controlling factor.

Figure 60 shows the relation between capacitor kva per kilowatt gained and the increase in kilowatts carrying capacity which can be realized without increasing current magnitude. The curve shows the gains that may be made in kilowatt line capacity for the same current by adding capacitor to cancel out the reactive current. It also shows the kva of capacitor required for different load power factors.

Referring to Fig. 60, an increase of 30 per cent in the load is a per unit gain of 0.3. Reading above the point where the vertical line intersects the 70 per cent power-factor line, then horizontal to the other scale, we note that the capacitor kva required per kilowatt gained is 2.45. Since the assumed capacitor cost is $10 per kva installed, we have $24.50, or the cost of capacitors per kilowatt gained. It is of interest to note that the cost per kilowatt gained is determined only by the per cent increase in kilowatt desired, the uncorrected load power factor, and the cost of capacitors per kva.

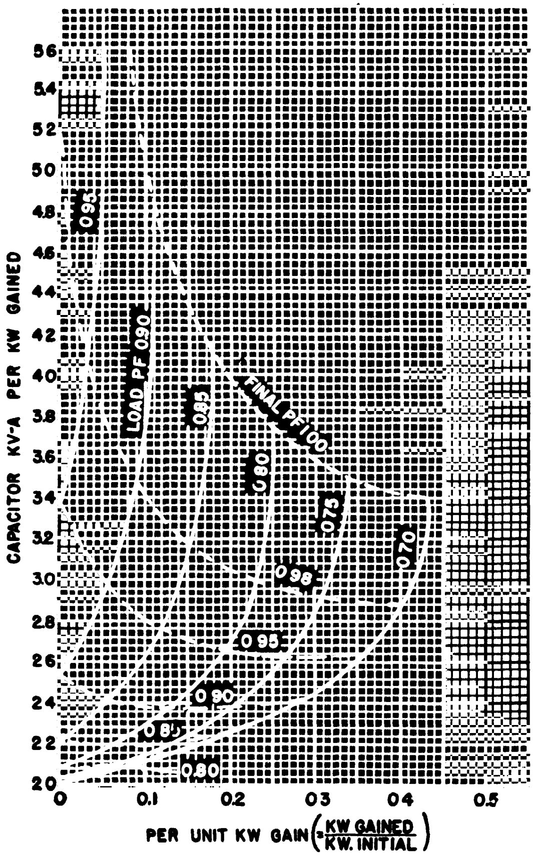


FIG. 60. Kilowatts gained by addition of capacitors where current is the limiting factor.

Carrying the example further, suppose the original kilowatt equaled 769, thus making the 30 per cent increase value 1,000 kw. Assume the capacitor cost $10 per kva installed. The capacitor kva per kilowatt gained = 2.45. The capacitor kva = 2.45 × (1,000 − 769) = 566, and the cost of the capacitor would be 566 × $10 per kva = $5,660.

Figure 60 also shows limit conditions at once, as, for example, assume that one considers the possibility of a 30 per cent gain in kilowatts for the same line current when the power factor is already 80 per cent. By referring to Fig. 60 it will be seen that a vertical line above the 0.3 gain point does not intersect the power-factor curve of 80 per cent; therefore a gain of 30 per cent cannot be obtained. The maximum gain is 25 per cent, giving a final power factor of unity. This would require 3.75 capacitor kva per kilowatt gained. If the power factor is 70 per cent it is possible to gain as much as 43 per cent and with 3.4 capacitor kva per kilowatt gained.

The new power factors are shown by the dotted line in Fig. 62.

KILOWATT GAINS IN LINE CAPACITY WHERE VOLTAGE IS THE LIMITING FACTOR

Delivered voltage is often the factor which sets the load limit of a circuit.

In investigating the practicability and economics of applying shunt capacitors for increasing load limits on this type of equipment, it is well to note that while a mere increase in voltage can perhaps be obtained at less cost by other means, such as step boosters, the shunt capacitor may none the less be the more economical. In addition to releasing system capacity by reducing voltage drop, the shunt capacitor also usually releases system capacity in other parts of the system by reducing current magnitude and voltage drop in those other parts. For example, the installation of capacitors on several primary distribution feeders whose load is limited by voltage drop may appear unjustified if only the increase in feeder load is considered; but the capacitors may prove a decidedly economical investment when we consider the reduction of current magnitude in other parts of the system such as substation transformers, cables, and finally (and very important) the generating station or supply. The dollars per kilowatt invested in generation is a large percentage of total system investment and a release of generating capacity, due to a reduction in current magnitude by means of capacitors applied out on the distribution system, is a most important point.

With the above in mind it is clear that in investigating the economics of shunt capacitors it is essential to consider the system capacity released in both types of equipment—where load limit is dictated by current magnitude and voltage drop—even though the immediate benefit may appear to be only one type.

EFFECT OF R/X RATIO ON LINE DROP

When the load current drawn by capacitors is supplied from equipment which possesses inductive reactance, fundamental considerations show that the voltage on the load side of equipment is higher than it is without the capacitor current, by an amount which can be taken with reasonable accuracy as the inductive reactance of the equipment times the line current taken by the capacitors. Obviously, if the amount of load connected to that equipment is limited by the voltage drop, then a larger load can be connected if shunt capacitors are applied. Analysis shows that the kw gained per capacitor kva depends only on the load power factor and the ratio of equipment resistance to the reactance. This means that once we know the load power factor and the ratio of equipment R to X, then the kw gained, per capacitor kva, is immediately fixed and does not depend on the percentage increase in kw. This unit cost per kw gained can readily be determined from Fig. 61, which also shows the linear variation with the ratio of R to X for various load power factors.

APPLICATION OF SHUNT CAPACITOR TO DISTRIBUTION CIRCUITS

In applying capacitors to a distribution system it is well to consider the voltage that will prevail during light loads.

Before applying capacitors it is desirable to obtain measurements by graphic instruments of kilowatts and reactive kva. After tentatively choosing a capacitor kva on the basis of peak-load requirements, the result at light loads may be readily calculated. If before correction the system lagging reactive kva does not vary over a wide range, which is usually the case, there is no need of considering reduction in capacitor kva. If before correction, the lagging reactive kva does vary over a wide range it may be desirable, rather than sacrifice the peak load improvements, to install a portion of the capacitors in concentrated banks with automatic switching control actuated by line voltage or line current.

As shown in Fig. 61 the R/X ratio determines the magnitude of the drop for a given load power factor. This is further brought out in Fig. 62.

The increase in kilowatts that can be supplied over a given circuit when capacitors are added to maintain the same voltage at the receiving end is illustrated by the following example.

Example. Assume the circuit is a 4-kv class using 4/0 bare stranded copper cable with the following characteristics:

Equivalent spacing = 33.6 in.
Resistance per mile = 0.303 ohms.
Reactance per mile = 0.629 ohms.

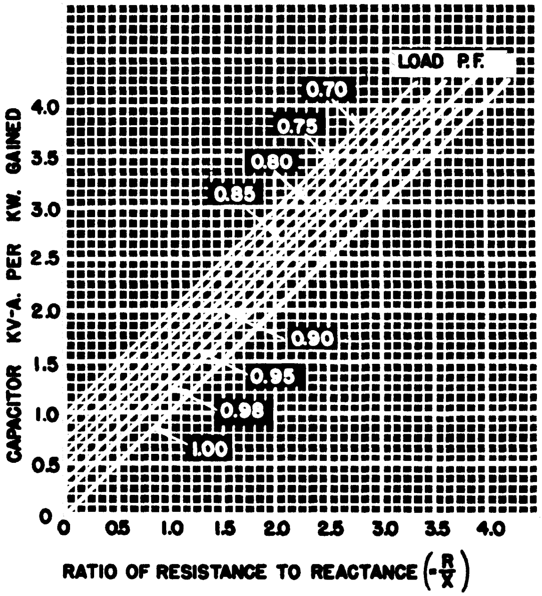


FIG. 61. Kilowatts gained by addition of capacitors where voltage is the limiting factor.

$$\frac{R}{X} = \frac{0.303}{0.629} = 0.483$$

Assume the load power factor is 80 per cent load $\tan \theta_L = 0.75$.

$$\frac{\text{Ckva}}{\text{Kw gained}} = \frac{R}{X} + \tan \theta_L$$

where R and X = resistance and reactance of line from point of capacitor installation to power source.
θ_L = original power-factor angle of load, assumed constant.

Then

$$\frac{\text{Ckva}}{\text{Kw gained}} = 0.483 + 0.75 = 1.233$$

and if installed three-phase capacitors = 300 kva,

$$\text{Kw gained} = \frac{300}{1.233} = 243$$

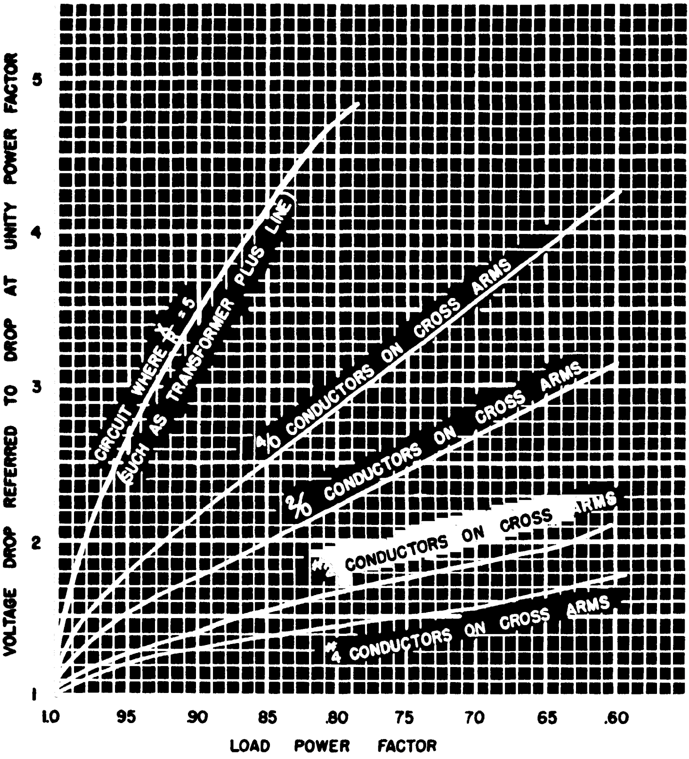


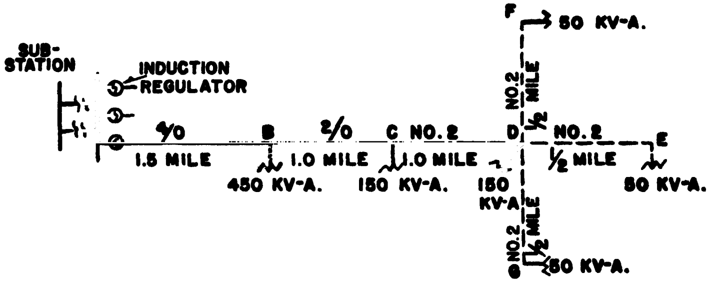
FIG. 62. Variation in voltage drop with load power factor for a fixed load in kilowatts.

The following procedure illustrates the application of shunt capacitors to distribution circuits.

Consider a regulated feeder (Fig. 63) having satisfactory voltage conditions, voltage at customers' premises being held within 95 and 105 per cent. Regulator operating at maximum 10 per cent boost; substation fully loaded; load on system is expected to grow.

Capacitor kva chosen equal to minimum reactive kva (Fig. 64) at substation. Calculations show:

1. Voltage conditions on feeder, regulated and unregulated, with and without capacitors, before load increase takes place.
2. Kilowatt or kva capacity released in feeder on basis of constant voltage drop.
3. Kilowatt or kva capacity released in substation, thermal capacity being the limitation.
4. Approximate reduction in feeder copper losses, assuming no load change, *i.e.*, before load increase takes place.



4160 VOLT-3 PHASE-DISTRIBUTION FEEDER WITH SINGLE-PHASE LATERALS CONNECTED BETWEEN LINE AND NUETRAL.

LEGEND:
——— = 3 PHASE—4160 VOLTS
- - - - = 1 PHASE—2400 VOLTS
FULL LOAD = 900 KV-A. AT .8 P.F.—(720 KW.; 540 RKV-A.)
LIGHT LOAD = 270 KV-A. AT .6 P.F.—(160 KW.; 220 RKV-A.)

FIG. 63. Typical load distribution on a feeder.

The feeder load data are as follows:

Time	Kw	Kvar	Kva
Midnight	220	300	370
2	170	240	290
4	160	220	270
6	160	230	280
8	200	280	350
10	230	290	370
Noon	360	310	480
2	630	420	760
4	650	460	800
6	720	540	900
8	650	520	830
10	370	380	530
Midnight	220	300	370

$$\text{Voltage drop on feeder in per cent} = \frac{\text{kva}\,(R\cos\theta + X\sin\theta)\times d}{10\times(\text{kv})^2}$$

where kva = kva of circuit; for three-phase circuit this is three-phase kva, and for single-phase circuit, it is single-phase kva.

R = resistance of line in ohms per mile.*

X = reactance of line in ohms per mile.*

θ = power factor angle of load.

d = length of line in miles.

kv = line-to-line voltage in kilovolts.

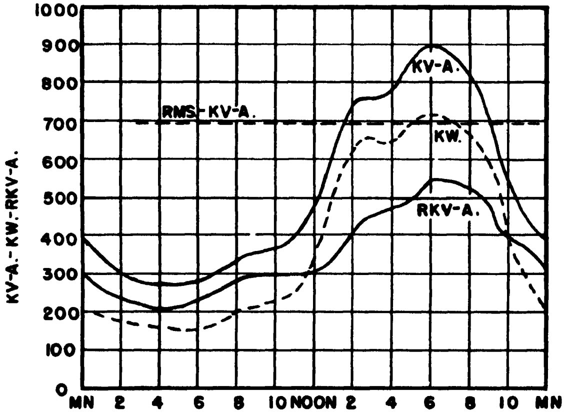


FIG. 64. Assumed daily load curves.

Sample Calculation 1. Consider three-phase Section *B-C* (Fig. 63); θ at full load, with 2/0 conductor, 33.6 in. equivalent spacing.

Three-phase kva = 450

R = 0.48 ohms per mile

X = 0.66 ohms per mile

d = 1.0 mile

Kv = 4.16

$\cos\theta$ = 0.8

$\sin\theta$ = 0.6

$$\text{Per cent voltage drop} = \frac{450\,(0.48\times 0.8 + 0.66\times 0.6)\times 1.0}{10\times 4.16^2} = 2.0 \text{ per cent}$$

Sample Calculation 2. Consider single-phase section *D-E;* at full load with No. 2 conductor.

---

*Note that for single-phase circuit R and X are equal to twice values per conductor.

$$\begin{aligned}
\text{Kva} &= 50\\
R &= 2\ (0.96) = 1.92 \text{ ohms per mile}\\
X &= 2\ (0.67) = 1.34 \text{ ohms per mile}\\
d &= 1.0 \text{ mile}\\
\text{Kv} &= 2.4\\
\cos\theta &= 0.8\\
\sin\theta &= 0.6
\end{aligned}$$

$$\text{Per cent voltage drop} = 50\,\frac{(1.92 \times 0.8 + 1.34 \times 0.6) \times 1.0}{10 \times 2.4^2} = 1.0 \text{ per cent}$$

The voltage drops in the other sections are shown in Table 13.

TABLE 13. VOLTAGE DROP ON OTHER LINE SECTIONS

Feeder section	Miles	Full load		Light load	
		Kva	Per cent drop	Kva	Per cent drop
A-B	1.5	900	4.9	270	1.60
B-C	1.0	450	2.0	135	0.64
C-D	1.0	300	2.1	90	0.47
D-E	0.5	50	1.0	15	0.30
D-F	0.5	50	1.0	15	0.30
D-G	0.5	50	1.0	15	0.30

These drops are plotted in Fig. 65, which also gives the voltage conditions with the regulator in service.

It may be noted from Fig. 65 that the full-load drop from the substation to the last distribution transformer on the single-phase taps is 10 per cent. In this particular case, the substation voltage is 100 per cent, so that the lowest voltage in the primary circuit is 90 per cent. If we allow an additional 5 per cent voltage drop for the secondary circuit, composed of the distribution transformer, secondary main, and service, the lowest voltage at the customer's premises is 85 per cent, which is considered too low. In several states, laws require that the voltage at the customer's premises be held within certain prescribed limits, usually ± 5 per cent of normal voltage. This permits a minimum voltage at the customer's premises of 95 per cent and a maximum of 105 per cent. The permissible voltage variation in the primary circuit in the load zone is 5 per cent, the upper limit being 105 per cent and the lower limit 100 per cent. If an induction regulator is used to maintain these voltage limits, a tolerance of ±1 per cent voltage must be allowed, so that the actual permissible voltage variation in the load zone is 3 instead of 5 per cent.

In this particular case, it is assumed that the permissible primary voltage variation between the first and last transformer is 5 per cent, including the regulator tolerance. It will be noted that these voltage limits are satisfied by means of an induction regulator located at the substation and operated at full 10 per cent boost. With the proper degree of compensation, it can be seen that the voltage variation at full load and light load meets the requirements.

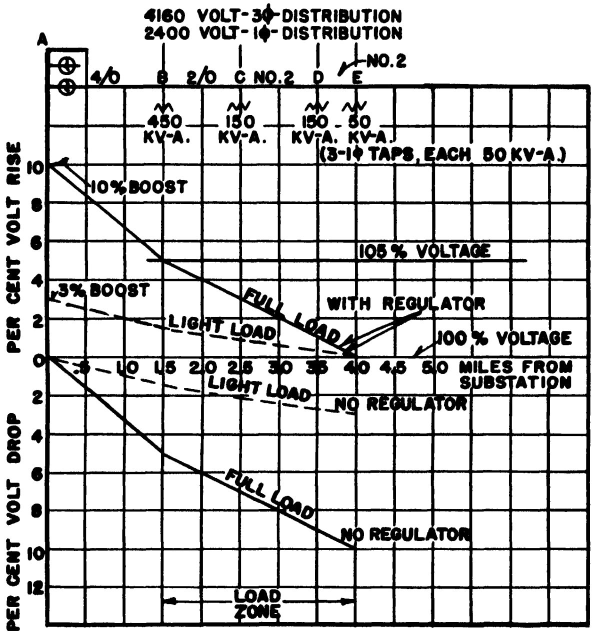


FIG. 65. Voltage conditions on a typical feeder with and without regulator.

Thus it may be seen that the voltage conditions on the particular feeder are satisfactory and that no voltage correction is required under the present load conditions. When the load is increased, it is evident that the voltage limitations will be exceeded, since the regulator is already operating with maximum boost. By installing capacitors, it is possible to release kilowatt capacity in feeders without increasing the voltage drop. In addition, the kilowatt capacity released at the substation will permit an increase in load without exceeding the rating of the substation.

Kva and Location of Capacitors. Assume that the kva of capacitors chosen is equal approximately to minimum kvar on the feeder, namely 220 kva. Choosing standard three-phase increments of 45 kva, the capacitor total will be 270 kva. These capacitors will be distributed at the loads. The distribution of capacitors is shown in Fig. 66.

The benefits resulting from these capacitors may be readily calculated. First, consider the voltage-drop reduction due to the voltage rise produced by the capacitors. It is well to calculate the voltage conditions on the feeder after the capacitors are installed, particularly at light load, in order to make certain the voltage limitations are not exceeded. In the problem under consideration capacitors are installed to take care of an expected load increase. Ultimately, when the load has increased to the point permitted by the capacitors, the voltage conditions will be the same as those before the capacitor application; but immediately after the capacitor application it is evident that the voltage conditions will be different. Figure 67 shows the voltage rise produced by the capacitors and Fig. 68 shows the net voltage drops, based on assumption of no load increase.

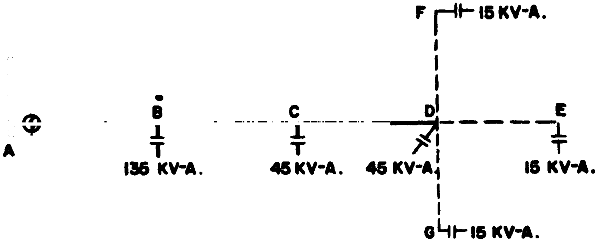


FIG. 66. Distribution of capacitors on typical feeder.

Voltage Rise Produced by Capacitors. The voltage rise is, with a fair degree of accuracy, equal to the product of capacitor current and the reactance of the circuit. In terms of capacitor kva and line voltage, we have

$$\text{Per cent voltage rise} = \frac{\text{Ckva} \times X}{10 \times \text{kv}^2}$$

where Ckva = capacitor kva, three-phase in three-phase circuit and single-phase in single-phase circuit.

X = total reactance, ohms.*

kv = line-to-line kilovolts.

* Note for single-phase circuit X = twice value per conductor.

Sample Calculation 1. Consider three-phase section *B-C*, Fig. 66.

$$\begin{aligned}\text{Ckva} &= 135\\ X &= 0.66 \text{ ohms per mile} \times 1.0 \text{ mile}\\ &= 0.66 \text{ ohms}\\ \text{Kv} &= 4.16\end{aligned}$$

$$\text{Per cent voltage rise} = \frac{135 \times 0.66}{10 \times 4.16^2} = 51 \text{ per cent}$$

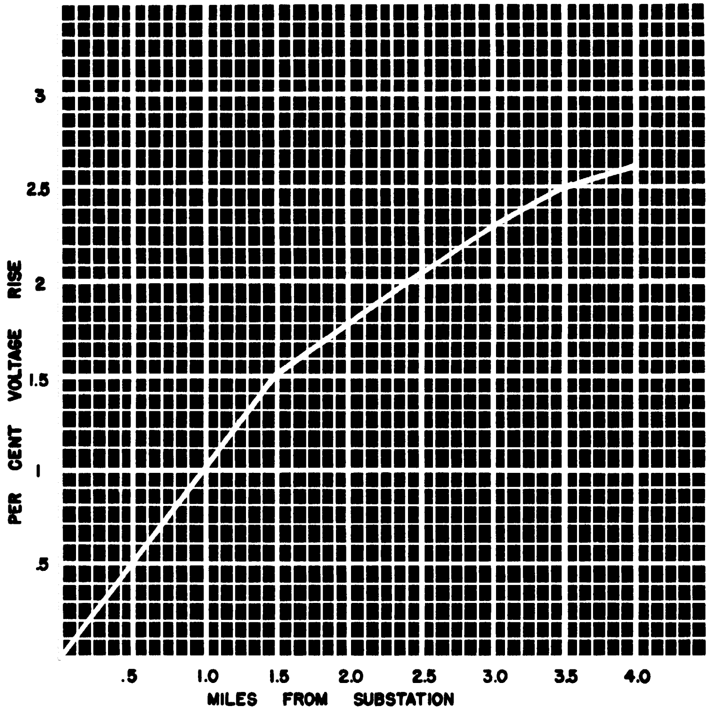


FIG. 67. Voltage rise produced by capacitors.

Sample Calculation 2. Consider single-phase section *D-E*.

$$\begin{aligned}\text{Ckva} &= 15\\ X &= 2\ (0.70) \text{ ohms per mile} \times 0.5 \text{ mile}\\ &= 0.70 \text{ ohms}\\ \text{Kv} &= 2.40\end{aligned}$$

$$\text{Per cent voltage rise} = \frac{15 \times 0.70}{10 \times 2.4^2} = 0.18 \text{ per cent}$$

The voltage rise in the other sections is shown in Table 14 and is plotted in Fig. 67.

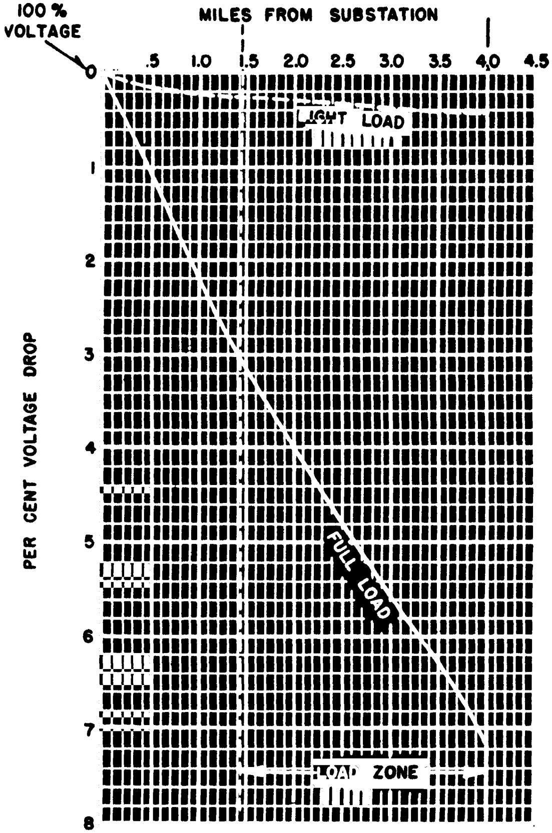


FIG. 68. Net voltage drop with capacitors but without regulators.

TABLE 14. VOLTAGE RISE ON OTHER SECTIONS OF LINE

Feeder section	Miles	Ckva	X, ohms	Voltage rise, per cent	Cumulative voltage rise, per cent
A-B	1.5	270	0.95	1.50	1.5
B-C	1.0	135	0.66	0.51	2.0
C-D	1.0	90	0.70	0.36	2.4
D-E	0.5	15	0.70	0.18	2.6
D-F	0.5	15	0.70	0.18	2.6
D-G	0.5	15	0.70	0.18	2.6

Net Voltage Drops with Capacitors. To obtain the net voltage drop, the voltage rise of Fig. 67 is superimposed on the voltage drop shown in Fig. 65. The regulation with and without regulators is shown in Figs. 68 and 69 and Tables 15 and 16, respectively.

TABLE 15

Location	Miles from substation	Voltage drop without regulators and capacitors, per cent		Voltage rise due to capacitors, per cent	Net voltage drop with capacitors without regulators, per cent	
		Full load	Light load		Full load	Light load
A	0	0	0	0	0	0
B	1.5	4.9	1.6	1.5	3.4	0.1
C	2.5	6.9	2.2	2.0	4.9	0.2
D	3.5	9.0	2.7	2.4	6.6	0.3
E	4.0	10.0	3.0	2.6	7.4	0.4
F	4.0	10.0	3.0	2.6	7.4	0.4
G	4.0	10.0	3.0	2.6	7.4	0.4

TABLE 16

Location	Miles from substation	Net per cent voltage with capacitors and regulators, 7.4 per cent boost at full load, 0.4 per cent boost at light load, bus voltage = 100 per cent	
		Full load	Light load
A	0	107.4	100.4
B	1.5	104.0	100.3
C	2.5	102.5	100.2
D	3.5	100.8	100.1
E	4.0	100	100
F	4.0	100	100
G	4.0	100	100

It is assumed that the substation voltage is 100 per cent. On this basis, in order to keep within the primary voltage limits of 100 to 105 per cent in the load zone, it is evident that the regulator must boost the voltage by 7.4 per cent at full load and 0.4 per cent at light load. It will be noted from Fig. 69 that the voltage conditions have been improved by the capacitor application, since the maximum voltage difference between the first and last customers has been reduced from 5 to 4 per cent.

Economic Gains.

1. *Kilowatt Capacity* (Δ *kw*) *Released in Feeder.* On the basis of the same voltage drop before and after application of capacitors:

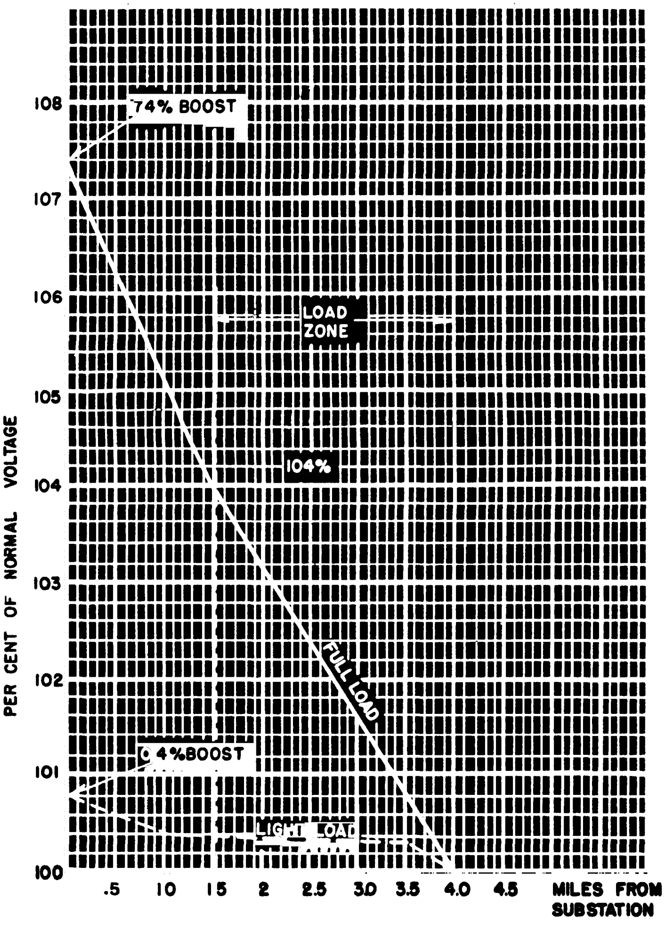


FIG. 69. Net voltage variation with capacitors and regulators.

$$\frac{\text{Ckva}}{\Delta\ \text{kw}} = R/X + \tan\theta \qquad \text{or} \qquad \Delta\ \text{kw} = \frac{\text{Ckva}}{R/X + \tan\theta}$$

where Ckva = capacitor kva.

R/X = ratio of resistance to reactance from capacitor installation to substation.

θ = power factor angle of load, assumed fixed.

Sample Calculation. Consider kilowatts released by 45-kva three-phase capacitor unit located at C.

$$\text{Resistance} = (1.0 \times 0.481 + 1.5 \times 0.303) = 0.94 \text{ ohms}$$
$$\text{Reactance} = 1.0 \times 0.657 + 1.5 \times 0.629) = 1.59 \text{ ohms,}$$
$$R/X = \frac{0.94}{1.59} = 0.59$$
$$\tan\theta = 0.75$$
$$R/X + \tan\theta = 0.59 + 0.75 = 1.34$$
$$\Delta \text{ kw} = \frac{45}{1.34} = 34 \text{ kw}$$

TABLE 17. KILOWATTS RELEASED BY EACH CAPACITOR INSTALLATION

Location	Ckva	R, ohms	X, ohms	R/X	Δ kw
B	135	0.46	0.93	0.49	110
C	45	0.94	1.59	0.59	34
D	45	1.90	2.29	0 83	28
E	15	3.81	3.69	1.03	9
F	15	3.81	3.69	1.03	9
G	15	3.81	3.69	1 03	9

In the same manner, the kilowatts released by the other capacitor installations are shown in Table 17.

$$\text{Total load increase} = \frac{199}{0.8} = 250 \text{ kva} \quad \text{or} \quad \frac{250}{900} \times 100 = 28 \text{ per cent}$$

without changing voltage drop.

Assuming the primary distribution is valued at \$30 per kva, the total capacity released by the capacitors is worth 30 × 250 = \$7,500. On the basis of a 15 per cent carrying charge, the annual worth is 0.15 × 7,500 = \$1,100 per year.

2. *Reduced Feeder Losses.* Assuming no change in load, the reduction in feeder copper losses in kilowatts is given by the relation

$$\frac{\text{Ckva} \times R\,(2\,\text{kva} \sin\theta - \text{Ckva})}{1{,}000 \times \text{kv}^2}$$

where Ckva = three-phase capacitor kva.
kva = three-phase load kva (rms value for typical 24-hr period, *i.e.*, square root of average squared kva).
R = resistance from substation to load center, ohms.

θ = power-factor angle of load corresponding to rms value of load.
kv = line-to-line kilovolts.

From the load curve (see Fig. 64)

$$\begin{aligned} \text{kva} &= 700 \\ \text{Ckva} &= 270 \\ R &= 0.93 \text{ ohms (approximately)} \\ \sin\theta &= 0.65 \\ \text{Kv} &= 4.16 \end{aligned}$$

The three-phase reduction in feeder copper losses is then

$$\frac{270 \times 0.93\,[(2 \times 700 \times 0.65) - 270]}{1{,}000 \times 4.16^2} = 9.35 \text{ kw}$$

Annual reduction = 9.35 × 8,760 = 83,000 kwhr.

Assuming copper loss is worth 1 cent per kwhr, savings = $1,510 per year.

3. *Released Substation Capacity, Δ kva.* Since current magnitude or heating is the limitation in this case, the increase in kva capacity of the substation is given by the formula

$$\Delta \text{ kva} = \text{kva}_1 \left[\frac{\text{Ckva}}{\text{kva}_1} \sin\theta - 1 + \sqrt{1 - \left(\frac{\text{Ckva}}{\text{kva}_1}\right)^2 \cos^2\theta} \right]$$

where Δ kva = increase in kva capacity at the original power factor.
Ckva = three-phase capacitor kva
kva_1 = three-phase kva rating of substation
$\cos\theta$ = original power factor

To obtain the kva capacity released in the substation, it is necessary to consider the capacitors installed on all the feeders coming out of the substation The released capacity may then be allocated to each of the feeders in proportion to the installed capacitor kva on the feeder. In the problem under consideration, there is a total of five feeders, each having approximately 270 kva of capacitors installed. The capacity of the substation is 5,000 kva The total substation capacity released is

$$\Delta \text{ kva} = 5{,}000 \left[\frac{5 \times 270}{5{,}000} \times 0.6 - 1 + \sqrt{1 - \left(\frac{5 \times 270}{5{,}000}\right)^2 \times 0\,8^2} \right] = 700 \text{ kva}$$

or

$$\frac{700}{5} = 140 \text{ kva per feeder}$$

Assuming the substation is valued at $35 per kva, the capacity released per feeder is worth 35 × 140 = $4,900 investment in new equipment. On the basis of a 15 per cent carrying charge, the annual charges are 0.15 × 4,900 = $735 per year.

Increased Transmission and Generator Capacity. The kva capacity released in the transmission system and generators by the application of capacitors is computed in the same manner as that for the substation, assuming current magnitude is the limitation for the transmission system as well as the generators.

This released capacity is of value only if an immediate expenditure in new equipment is deferred, in which case the average cost of generation may be taken as $134 per kva and of transmission $87 per kva.

TABLE 18. SUMMARY OF ECONOMIC VALUE OF 270-KVA SHUNT CAPACITORS ON DISTRIBUTION FEEDER

Released feeder capacity (carrying charges)	$1,100 per year
Reduced feeder copper losses	1,510 per year
Released substation capacity (carrying charges)	735 per year
Released transmission and generation capacity	No value at present
Cost of 270 kva capacitors at $10 per kva	2,700

However, in the problem under consideration, both the transmission and generator capacities are ample to meet the anticipated load growth, so that no value is placed on the released capacity for the time being.

Table 18 is a summary of the economic value of the 270 kva of capacitors on the distribution feeder. It may be noted that the capacitors are more than paid for in the first year of operation through the economies effected.

The foregoing example illustrates the method of distributing the capacitor units at the loads. Maximum voltage correction, however, can be obtained by locating the capacitors at or near the ends of the feeders. For example, if all of the 270 kva of capacitors are located at point *D*, which is the end of the three-phase feeder, the voltage rise from the substation to point *D* is 3.6 per cent, compared with the value of 2.4 per cent obtained with the capacitors distributed at the loads. The kw capacity released in the substation and transmission and generating systems is the same as before. On the feeder itself, since a greater voltage rise is obtained, a greater load increase is permitted without exceeding the primary-voltage limitations. If current magnitude were the controlling factor on the feeder, instead of voltage drop, then the same amount of load relief is afforded to section *A-B* of the feeder, since the same capacitor kva (270) flows through this part of the circuit in both cases. On sections *B-C* and *C-D* of the feeder the situation is different, because now 270 kva of capacitors are connected instead of 135 kva and 90 kva, respectively. In this particular case, greater load relief would be offered, since the power factor of the circuit is raised to approximately unity at full load. In addition, it so happens that the feeder copper losses for these sections are lower than before. On the whole, it is evident that in this particular case, greater benefits can be derived by locating the capacitors at the end of the three-phase feeder.

The above example is not intended to prove that it is better from the economic standpoint to locate capacitors at the ends of feeders rather than at the loads. Large capacitor concentrations may cause some feeder sections to operate at leading power factor, with consequent increased feeder losses and possible overload on the feeder. Moreover, the voltage rise produced by the capacitors may cause the voltage at light load to be too high. This emphasizes the need for determining the voltage conditions on the feeder with and without capacitors. Furthermore, when considering the voltage rise produced by capacitors due allowance must be made for the fact that considerable load unbalance may exist at light load which would make the voltage on the least loaded phase higher than that anticipated on the basis of a balanced load.

From the foregoing it is evident that no fixed rules can be stated regarding the location of the capacitor banks. Each case is different and requires a complete study. It is important to consider the economies of the application, and it is believed that the methods outlined on the previous pages will serve as a useful guide. A certain degree of judgment is required in all applications, particularly in those cases where the exact voltage and load conditions are not known. All factors should be considered. Where voltage correction is desired, the cost of obtaining this correction by means of capacitors should be compared with other means, such as the construction of a new feeder or the use of other regulating devices. Wherever possible, capacitors should be credited with the kilowatt capacity released in all equipment between the capacitor installation and the generating station. Considerable savings are sometimes effected by the investment deferred on new equipment through the use of capacitors.

When kvar is supplied over a considerable distance to an inductive load the kvar needed may be 25 or 50 per cent greater due to the I^2X drop in the system. This should be given careful consideration in locating the capacitors on the system, so as to keep the required kvar in capacitors to a minimum value. This advantage must be weighed against other advantages associated with large groups of capacitors at important load centers.

Bibliography

ALIMANSKY, M. I.: Capacitors for Power Factor Improvement, *Power*, vol. 85, October, 1941.

ALLEN, E.: Static Capacitors Supply Wattless Current, Increase System Capacities, Cut Costs, *Elec. Light & Power*, vol. 15, pp. 42–44, May, 1937.

APPLEMAN, G.: Traveling Capacitors Are Versatile Tool, *Elec. World*, vol. 115, pp. 464–465, 538–539, February 8, 1941.

BANKUS, J.: Effects of Low Power Factor Loads on Distribution Feeders and Methods for Correction, *Elec. West*, vol. 72, pp. 123–127, June, 1934.

BEKKU, S.: Power Condensers in Japan, *Int. Conf. on Large High Voltage Systems (C.I.G.R.E.)*, vol. 3, report 123, pp. 1–16, 1939.

BENSON, C. R.: CKVA, *Elec. West*, vol. 81, pp. 42–46, October, 1938.

BUELL, H. H.: Capacitors Transferred as Peak Load Shift, *Elec. West*, vol. 82, pp. 35–36, March, 1939.

BUTLER, J. W.: Capacitors and Circuit Performance, *A.I.E.E. Trans.*, vol. 60, p. 408, 1941.

BUTLER, J. W.: Kilowatts, Kilovars, and System Investment, *A.I.E.E. Trans.*, vol. 62, pp. 133–137, March, 1943.

BUTLER, J. W.: Shunt Capacitor Application Problems, *Gen. Elec. Rev.*, vol. 43, pp. 206–212, May, 1940.

BUTLER, J. W.: Synchronous Condensers or Capacitors, *Gen. Elec. Rev.*, vol. 44, pp. 429–437, August, 1941.

Capacitor Demand and KVA Installed, *Elec. Light and Power*, p. 80, June, 1942.

CASKY, A. D.: Current Control Broadens Capacitor Application, *Elec. Light & Power*, vol. 18, pp. 49–51, February, 1940.

CUTTINO, W. H.: Capacitors Reduce Losses and Raise Voltage, *Southern Power & Ind.*, vol. 59, pp. 115–118, October, 1941.

DOUGLASS, F. S.: Capacitors Release System Capacity, *Elec. World*, vol. 106, part I, pp. 3809, 3946, December 19, 1936.

DRAKE, C. W.: Power Factor Correction, *Diesel Power*, vol. 17, pp. 830, 832, 834, October, 1939.

DRAKE, C. W.: Power Factor Correction—When, Where, and How Much, *Elec. J.*, vol. 32, pp. 442–444, October, 1935.

GAMBLE, G. P., R. C. MORRIS, and A. W. HOWELL: Capacitors Preferred to Machine Reactive, *Elec. World*, p. 65, September 19, 1942.

GAMBLE, G. P., and F. M. STARR: Shunt Capacitors on Distribution Circuits, *Gen. Elec. Rev.*, vol. 39, pp. 466–474, October, 1936.

GEORGE, B. J.: Less Operating Difficulties, Bettered Power Factor, *Elec. World*, vol. 107, pp. 268–271, January 16, 1937.

HAUSSON, B.: Static Condensers for Power Circuits, *A.S.E.A. J.*, vol. 11, pp. 170–173, December, 1934.

HERMANN, C. C.: Locating Static Condenser for Best Results, *Southern Power & Ind.*, vol. 58, pp. 74–75, December, 1940.

HODDY, G. L., and M. J. MYLOTT: Capacitors Ease Peak on Municipal System, *Elec. World*, vol. 112, pp. 453–4, 514, August 12, 1939.

HOOKE, R. G.: Static Capacitors Save Investment Dollars—I, *Elec. World*, vol. 117, pp. 1108–1110, March 21, 1942.

LYTLE, C. M., and S. H. POLLOCK: Shunt Capacitors Reduce KVA Loads, *Elec. Light & Power*, vol. 15, pp. 52–54, November, 1937.

MARBURY, R. E.: Capacitors for Distribution Circuits, *Elec. J.*, vol. 34, pp. 103–106, March, 1937.

MARBURY, R. E.: Capacitors May Be Answer, *Southern Power & Ind.*, vol. 59, pp. 90–97, February, 1941.

MARBURY, R. E.: Inerteen Power Capacitors, *Elec. J.*, vol. 33, pp. 107–110, February, 1936.

MARBURY, R. E.: Need for Power Factor Correction, *Elec. J.*, vol. 32, pp. 377–379, September, 1935.

MARBURY, R. E.: Power Factor and Power Factor Economy, *Power Plant Eng.*, vol. 46, pp. 60–63, February, 1942.

MARBURY, R. E.: Power Factor Correction Releases Plant Capacity, *Elec. South*, March, 1942.

MARBURY, R. E.: Uses of Capacitors, *Elec. J.*, vol. 33, pp. 303–306, July, 1936.

MARBURY, R. E.: When You Install Capacitors, *Factory Management & Maintenance*, vol. 98, pp. 76–78, September, 1940.

MILLER, M. C.: Capacitors—Design, Application, Performance, *Elec. Light & Power*, vol. 16, pp. 46–50, October, 1938.

MILLER, M. C.: Performances of Distribution Capacitors, *Edison Elec. Inst. Bull.*, vol. 9, pp. 298, 328, July, 1941.

MILLER, M. C.: Seventeen Systems Report Smooth Capacitor Performance, *Elec. World*, vol. 113, pp. 289, 339–340, January 27, 1940.

MILLER, M. C.: Supplying Kilovar Loads for War Conservation and Economy, *Edison Elec. Inst. Bull.*, October, 1942.

MONTEITH, A. C.: System Outlay Saved Justifies Capacitors, *Elec. World*, vol. 107, pp. 2157–2159, June 19, 1937.

999 Capacitors in One 15,000 KVA Block, *Elec. World*, p. 93, September 19, 1942.

OLMSTEAD, L. M.: Capacitors and Automatic Boosters for Economical Correction of Voltage on Distribution Circuits, *A.I.E.E. Trans.*, vol. 58, p. 491, September, 1939.

PARSON, R. E., and M. LAWRENCE: Capacitors Release Hydro, Raise Voltage, *Elec. World*, vol. 112, pp. 716–717, 790, September 9, 1939.

PEARCE, C. T.: Power Factor Correction in Industrial Plants, *Elec. J.*, vol. 35, pp. 69–74, February, 1938.

POLLOCK, S. H.: Capacitors Increase Distribution Capacity, *Elec. World*, vol. 110, pp. 851–858, September 24, 1938.

RETTIG, V. G.: Basis for a Program of Capacitor Additions on a Growing Distribution System, *Edison Elec. Inst. Bull.*, vol. 8, pp. 387–394, August, 1940.

RETTIG, V. G.: Capacitors Programmed for Growing Distribution, *Elec. World*, vol. 114, pp. 78–80, July 13, 1940.

ROBERTS, J. F.: Capacitors Defer $135,000 Investment in Synchronous Unit, *Elec. West*, vol. 83, pp. 42–43, October, 1939.

ROSE, H.: Utilities' Interest in Shunt Capacitors, *Bull. Hydro Electric Power Commission of Ontario*, vol. 24, pp. 113-127, April, 1937.

RYDBECK, G.: Application of Static Condensers for the Production of Reactive Power, *A.S.E.A. J.*, vol. 15, pp. 90-102, August, 1938.

SCHULZE, H.: Power Factor Improvement by Condensers, *Int. Conf. on Large High Voltage Systems (C.I.G.R.E.)*, vol. 3, report 308, pp. 1-15, 1939.

SCOVILLE, M. E.: Maintenance of Capacitors, *Southern Power & Ind.*, December, 1942.

SEELY, T., and P. H. JEYNES: Capacitor Program for Distribution Betterment—I, II, *Elec. World*, vol. 114, pp. 380-382, August 10, 1940; pp. 455-457, August 24, 1940.

SELS, HOLLIS K., and THEODORE SEELY: Facilities for the Supply of Kilowatts and Kilovars, *A.I.E.E. Trans.*, vol. 61, p. 249, May, 1942.

SIMS, W. F.: Shunt Capacitors and Their Application, *Edison Elec. Inst. Bull.*, vol. 3, pp. 357-361, September, 1935.

SMITH, C. G.: Harmonics and Capacitors, *Elec. West*, vol. 85, pp. 40-43, November, 1940.

STARR, F. M.: Reduction of System Power and Energy Losses by Power Factor Improvement, *Gen. Elec. Rev.*, vol. 45, pp. 165-171, March, 1942.

STARR, F. M.: Rural KVA Profitably Released by Capacitors, *Elec. World*, vol. 110, pp. 1715, 1716, 1759, December 17, 1938.

STARR, F. M.: Secondary Versus Primary Capacitors, *A.I.E.E. Trans.*, vol. 58, pp. 228-242, May, 1939.

STARR, F. M.: Will They Do? The Record Speaks, *Elec. Light & Power*, vol. 19, pp. 46-50*a*, March, 1941.

Static Condensers for Power Factor Improvement, *A.E.G. Progress*, no. 4, pp. 74-6, 1932.

THOMPSON, H. W.: Capacitors Help Attleboro Lift Power Factor, Cut Peak, *Elec. World*, vol. 117, pp. 1337-1339, April 18, 1942.

VAN HORN, R. H., and W. S. HILL: Capacitors Prove Out in Decade of Service, *Elec. World*, vol. 106, pp. 889-890, March 28, 1936.

WOLF, H. B., and G. G. MATTISON: Mobile Capacitor Units for Emergency Loading of Transformers in Open Delta, *A.I.E.E. Trans.*, vol. 62, pp. 83-86, February, 1943.

WRIGHT, S.: Applying Shunt Capacitors to Distribution Systems, *Elec. J.*, vol. 34, pp. 195-199, May, 1937.

CHAPTER 6

FUSES, SWITCHES, AND CONNECTIONS USED WITH SHUNT CAPACITORS

INDIVIDUAL FUSES

It has been customary for many years to fuse capacitor units individually in a bank of units. This is done for three reasons. It is recognized that any piece of electrical equipment containing insulation is subject to failure of the insulation. Capacitors are designed sufficiently liberally so that these failures of the working insulation are limited to those occasional defects that are impossible to detect on manufacturing tests. Such failures rarely exceed two or three per thousand 15-kva units over a period of 10 years. Even with such a small per cent failure the probability of failures must be taken into account since single banks may be made up of several hundred 15-kva capacitor units.

If no individual fuse is used, the failure of a unit occurs and the bank of units will not be removed soon enough to avoid damage to adjacent units. It is obvious that an arc going on inside of a sealed unit will develop gas pressure quite rapidly due to the decomposition of the impregnating fluid. If this pressure is allowed to develop to the point of case rupture, the mechanical deformation of the unit is likely to damage adjacent capacitor units.

The first purpose of an individual capacitor-unit fuse is therefore to limit the duration of an arc inside a faulty capacitor unit. The second purpose of an individual fuse is to provide continuity of operation of the capacitor bank in case of a fault in one unit, so as to avoid shutting down the whole bank until the fault is located and removed. The third purpose of an individual fuse is to make it possible to locate a faulty unit easily in a bank containing many capacitor units and to avoid tests which might be necessary otherwise on each unit in the bank.

Breakers or main fuses do not serve the purpose of limiting the duration of the arc in the capacitor unit except on systems where the fault current is very limited or where the capacitor banks are small.

Examples are banks in which the fault current is 1,200 amp or less and the bank is 180 kva or less.

Individual fuses, like any fuse, must have sufficient interrupting rating for the application; otherwise the failure of the fuse to clear may result in as much damage to the rest of the bank as allowing a unit case to rupture.

In the case of banks of capacitors connected to systems capable of producing very high fault currents the fuse may be one having high rupturing capacity, or the capacitors may be connected in such a way as to greatly reduce the probability of high fault current.

Where the capacitors are connected phase to phase, the probable fault current may be limited by connecting capacitor units in series, as for example, three 2,400-volt units may be connected in series on a 7,200-volt system instead of 7,200-volt units phase to phase. The probability of a complete phase fault is sufficiently remote to justify the risk involved if fuses having limited rupturing capacity are used.

Another method is to star-connect the capacitor units and leave the capacitor neutral ungrounded. With this arrangement the current which flows in a short-circuited capacitor unit is limited by the impedance of the other two phases.

In either the series-connected arrangement or the star-connected scheme, one has to consider the disturbance in voltage distribution on the capacitor units. In some circuit arrangements the probability of unbalance is greater than in others. In some cases it is desirable to add additional equipment to detect and report a condition of excess voltage on the capacitor units. Where groups of capacitor units are connected in series, it is desirable to avoid the use of too few units in parallel; otherwise fuse operation will be uncertain, and once fuses have operated, the resulting increase in voltage on the remaining units will be excessive.

Y-CONNECTED BANKS

The first case that will be considered is the more common one of Y-connected units with neutral floating. In this arrangement a number of fuse operations in one phase will so unbalance the bank that the remaining units in this same phase will be subjected to overvoltage, or voltage in excess of the established operating limits. Figure 70 shows the voltage, in per cent of normal, which will be impressed on the remaining units in the phase from which units are removed by fuse operation.

If the line voltage corresponds to the capacitor-unit voltage rating, and since capacitors may operate at 105 per cent voltage, approximately 14 per cent of the units in one phase may be disconnected without exceeding the 105 per cent limit. Capacitor-unit failures are not sufficiently great to warrent any additional precautions other than an inspection of fuses occasionally. The voltage on the units, however, may be close to the 105 per cent limit to begin with. In such cases relay protection is desirable.

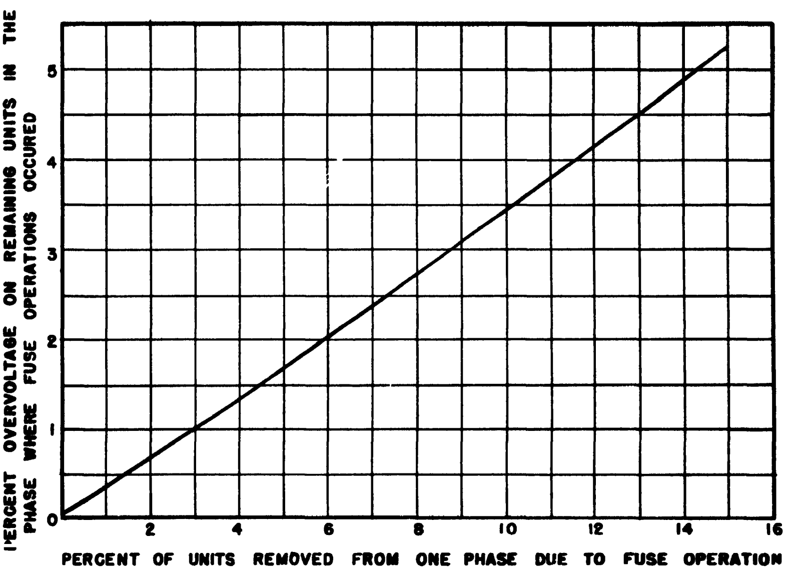


FIG. 70. Unbalanced voltage produced on a Y-connected bank of capacitors due to removal of capacitors in one phase.

Figure 71 shows a common method of detecting unbalance voltages on a Y-connected bank of capacitors. It consists of a relay energized by residual voltage of a Y-connected set of potential transformers with the secondary connected by a broken delta. When the bank of capacitors is balanced there is no potential on the relay coil. Any unbalance causes a voltage equal to three times the zero sequence potential to appear across the relay terminals. The operation of the relay may be used to trip the bank circuit breaker, or merely sound an alarm. The usual practice is to set the relay to operate when the voltage across any phase of the capacitor reaches some predetermined limit such as 105 per cent.

Y-CONNECTED BANKS USING CAPACITORS IN SERIES

In a Y-connected bank of capacitors as shown in Figure 72, the current flowing in a faulty unit is limited not only by the impedance of the other two phases but also by the impedance of the other units in the same phase. It is necessary, therefore, to connect each group of units in parallel as shown in Fig. 72 so that the current flowing in a faulty unit is not limited merely by another similar unit but by the combined impedance of the other group. The fuse should be one which will surely operate on the current thus obtained. Generally it is desirable

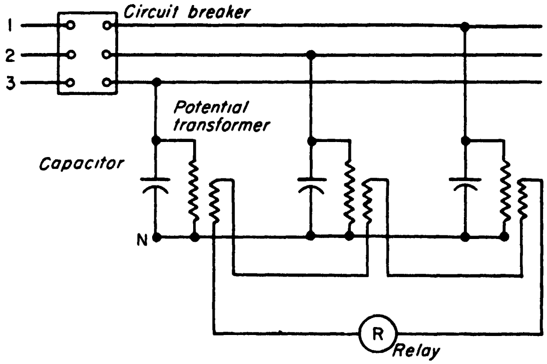


FIG. 71. Relay circuit for detecting unbalance phase voltage in a Y-connected floating neutral capacitor bank.

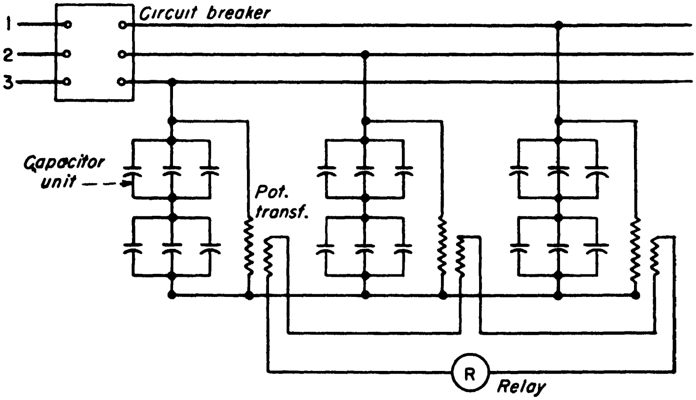


FIG. 72. Diagram showing a Y-connected bank of capacitors with series-connected units.

to limit the number to five or more in each group. A three-phase bank, if made up with 15-kva units, would therefore contain not less than 30 units, or 450 kva.

Obviously when banks are made up, such as shown in Fig. 72, the groups of units must be supported on insulated rails to give adequate insulation for the line voltage, and the potential transformers must be in a voltage class corresponding to line voltage but with a ratio based on phase-to-neutral voltage. Figure 73 shows a typical arrangement with groups of units mounted on insulated rails.

The need for relay protection is greater with the arrangement in Fig. 72 than in the case of Fig. 71 because the voltage goes up across the remaining units in a group where a fuse operation takes place, for two reasons. Not only does the voltage go up across the phase from which the unit was removed, but also the voltage distribution between the series-connected groups of the phase changes to place a higher voltage across the group where the fuse operation occurred.

Figure 74 shows the overvoltage on the phase in which the fuse operates to remove a capacitor, for an arrangement as shown in Fig. 72 with two, four, or six units in series on each phase. It should be noted, however, that we are chiefly interested in the voltage on the remaining units in the group of parallel units where the fuse is operated. The removal of this unit raises the impedance of this group considerably. Figure 75 gives the overvoltage impressed on the faulty group or the group from which units were removed. It should be noted that both Figs. 74 and 75 are in terms of the per cent of units removed from a group and a group is a plurality of units connected in parallel to operate at a given voltage.

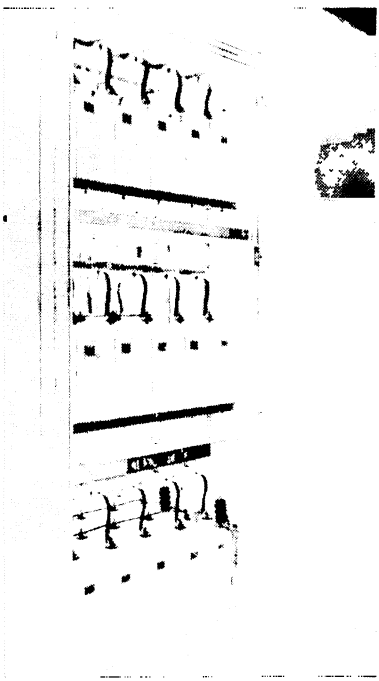


FIG. 73. Arrangement of fuses in a Y-connected bank with floating neutral.

It is generally desirable to avoid the use of many units in series, especially in small banks. The larger the bank, the larger the number of units that may be in parallel in a single group. The fewer in series, the larger the number that may be in parallel in a single group. The best arrangement is where the number in parallel is as large as feasible. A 25,000-volt bank of capacitors might be made up using 2,400-volt units, four parallel per group with six groups in series per phase, making a total of 24 2,400-volt units per phase. This arrangement is not recommended because four units in parallel will generally be undesirable when a number of groups are operated in series. It is far better to use 7,200-volt units and use two groups in series with 12 in parallel in each group. This gives positive fuse operation, and the rise in voltage following a fuse operation is not excessive.

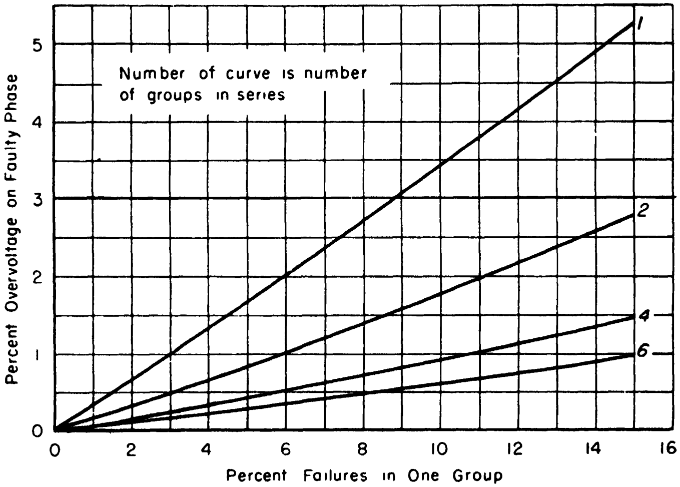


FIG. 74. Unbalanced voltage on phase of a Y-connected bank of capacitors, consisting of series groups per phase, and as a function of units removed from one group of units.

SWITCHING CAPACITOR BANKS

The factors which determine the selection of switches for connecting and disconnecting capacitor banks from the line are somewhat different from those determining the application of switches to other loads and devices. These factors which should receive consideration are as follows:

1. Continuous duty.
2. Overloads due to harmonies.
3. Inrush current.
4. Deenergizing transient.

Capacitors draw full-load current continuously so that the switch generally is not benefited by diversity factors.

Since the impedance of a capacitor decreases with increased frequency any wave-form distortion results in an increase in load current drawn by the capacitor.

Experience over many years has indicated that adequate allowance is made when the rating of the switch exceeds the nominal current of the capacitor by 35 per cent or more. This 35 per cent margin in the switch takes care of the most probable conditions likely to be encountered due to factors 1 and 2 above. This also takes into consideration the fact that the standard permissible working voltage over any 24-hr period may be 105 per cent of normal, which in itself may mean 105 per cent of normal current continuously. Also the manufacturing tolerance on capacitor units is 0 + 15 per cent with a probable value of plus 7.5 per cent. Thus, without any wave-form distortion, it is possible for the current to exceed the nominal value by 7.5 per cent plus 5 per cent, giving a total of 112.5 per cent current.

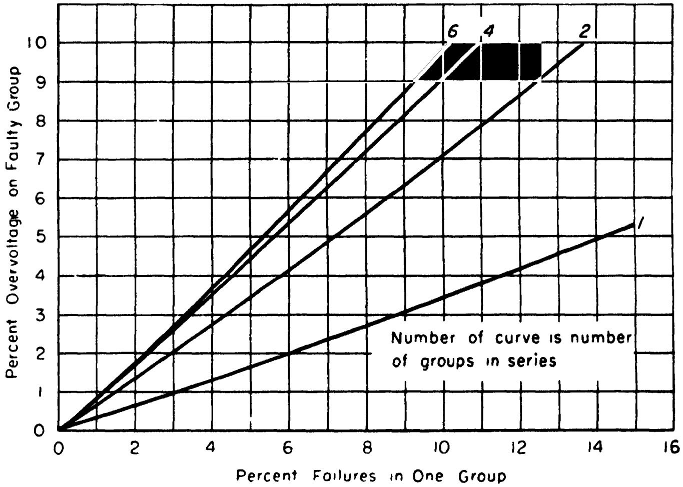


FIG. 75. Unbalanced voltage in one group of capacitors as a function of units removed from this group. Three-phase Y bank using groups in series per phase.

Some switches designed for industrial application are not rated on the basis of operating continuously at their current rating. When these switches are used with capacitors a margin greater than 35 per cent is necessary.

INRUSH CURRENT

When a capacitor is connected to an a-c voltage source a transient charging current flows, which is of large magnitude but short duration. The important part of this high-frequency transient current is usually all over in a small part of a fundamental cycle. The magnitude of this inrush is greatest if the voltage is passing through crest when the switch is closed. The inrush currents of three-phase capacitor banks are the same as the inrush current of one line to neutral phase alone. With a star-connected floating neutral bank or a delta bank, the inrush currents are also the same. Thus only one phase need be considered, and the inrush may be computed based on the application of a d-c voltage equal to the crest value of the a-c voltage.

Let us assume that a d-c voltage is applied to capacitor C, as shown in Fig. 76*A*. If the resistance were zero, the transient current would be a sine wave of high frequency, as shown in Fig. 76*B*. The presence of resistance causes the transient current to decay as shown in Fig. 76*C*, and the capacitor voltage approaches the applied voltage in an oscillatory manner, as shown by the dotted line. However, the resistance can usually be neglected with but small error in determining the first crest of transient current.

The classical expression for crest current magnitude is

$$I_{\text{max}} = \frac{E}{\sqrt{L/C}}$$

This expression may be put into another more useful form as follows:

The current will be expressed as the number of times the normal 60-cycle current of the capacitor switched on. The 60-cycle reactance X_L and X_C will be used in place of L and C, and these will be expressed in per unit (per cent/100) on the capacitor base in kva. When this is done the maximum transient current is given as

$$I_{\text{transient}} = \frac{1}{\sqrt{X_L \, X_C}} \times \text{normal current}$$

Since any shunt capacitor has 100 per cent reactance on its base kva this transient expression reduces to

$$I_{\text{transient}} = \frac{1}{\sqrt{X_L}} \text{ per unit}$$

$$X_C \text{ (in ohms)} = \frac{1{,}000 \, E_{LL}^2}{\text{kvar}}$$

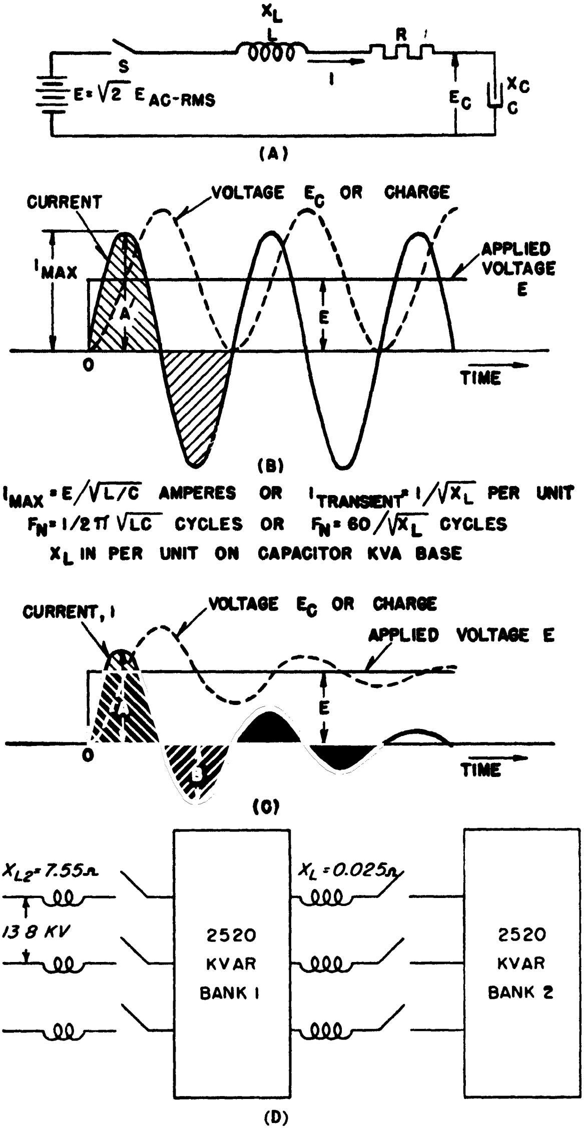


Fig. 76. Inrush current when switching a capacitor.

where E_{LL} = line voltage, kv.
kvar = capacitor bank.
X_C = line-to-neutral reactance, ohms.

$$X_L \text{ per unit} = \frac{X_L \text{ (in ohms)}}{X_C \text{ (in ohms)}}$$

As an example let us consider two 2,520-kva banks connected to a 13.8-kv line. The total source reactance is 7.55 ohms per line and the reactance between banks is 0.025 ohms per line. It makes no difference whether the capacitor bank is connected in star or delta since the calculations will be carried out on a line to neutral basis. This arrangement is shown in Fig. 76*D*.

Example (energizing bank number 1):

$$X_C \text{ (line to neutral)} = \frac{1{,}000 \times \text{kv}^2}{\text{kvar}} = \frac{1{,}000 \times 13.8^2}{2{,}520} = 75.5 \text{ ohms}$$

$$X_C = 1 \text{ per unit}$$

$$X_{L2} = \frac{7.55}{75.5} = 0.10 \text{ per unit}$$

$$I_{\max} = \frac{1}{\sqrt{X_C\ X_L}}\, I_n = \frac{1}{\sqrt{0.10}}\, I_n = 3.16\ I_n$$

$$I_n = \frac{\text{kvar}}{\sqrt{3}\,\text{kv}} = \frac{2{,}520}{\sqrt{3} \times 13.8} = 105.4 \text{ amp}$$

$$I_{\max} = 105.4 \times 3.16 = 334 \text{ amp rms}$$

As a check use

$$I = \frac{E}{\sqrt{L/C}}$$

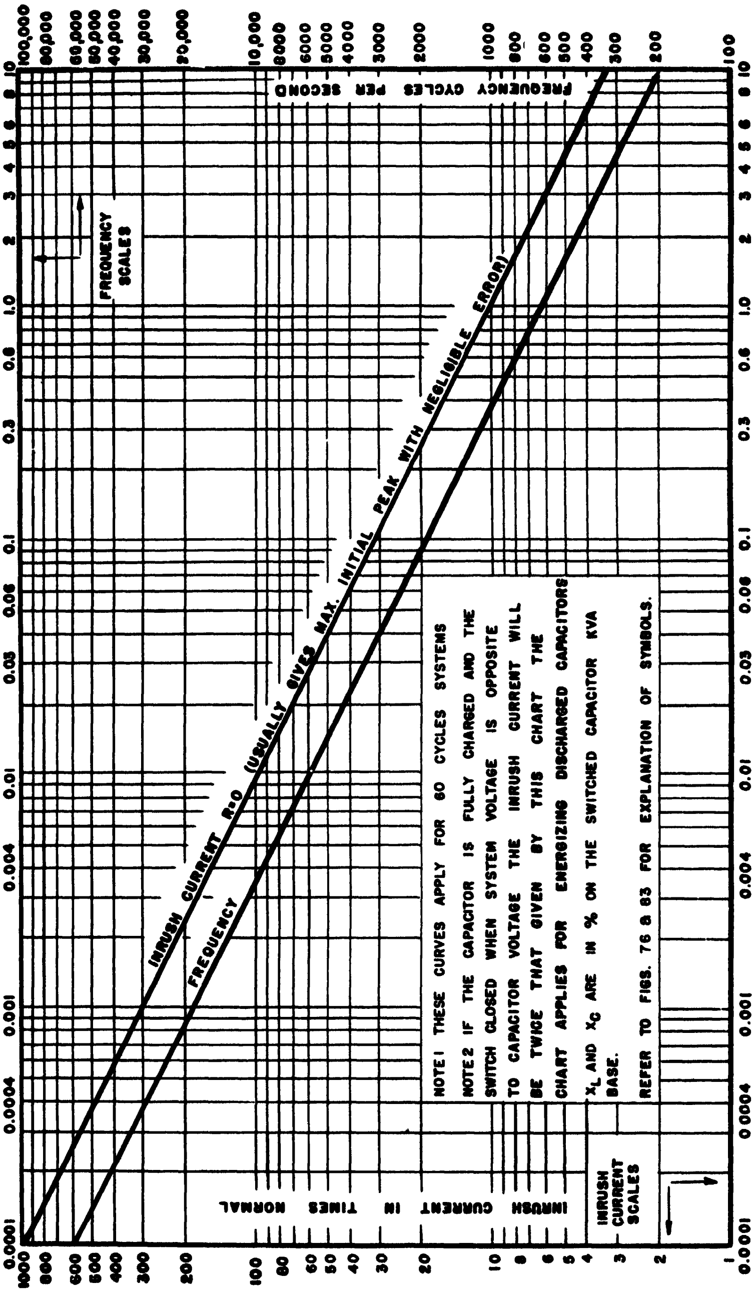
where E = line-to-neutral voltage.

$$L = \frac{X_C}{2\pi f} = \frac{7.55}{377} = 0.020 \text{ henry.}$$

$$C = \frac{1}{(X_C) \times (2\pi f)} = \frac{1}{75.5 \times 377} = 0.0000352 \text{ farad.}$$

$$I_{\max} = \frac{E}{\sqrt{L/C}} = \frac{13{,}800}{\sqrt{3 \times \dfrac{0.020}{0.0000352}}} = \frac{13.800}{1.732 \times 23.9} = 334 \text{ amp rms}$$

The relations brought out above are also expressed in another form in Fig. 77. This shows that with a source reactance of 10 per cent, that is, X_L = 10 per cent of capacitor kva with the base X_C, the inrush current will be 3.16 times the normal capacitor current.



NOTE 1 THESE CURVES APPLY FOR 60 CYCLES SYSTEMS

NOTE 2 IF THE CAPACITOR IS FULLY CHARGED AND THE SWITCH CLOSED WHEN SYSTEM VOLTAGE IS OPPOSITE TO CAPACITOR VOLTAGE THE INRUSH CURRENT WILL BE TWICE THAT GIVEN BY THIS CHART THE CHART APPLIES FOR ENERGIZING DISCHARGED CAPACITORS

X_L AND X_C ARE IN % ON THE SWITCHED CAPACITOR KVA BASE.

REFER TO FIGS. 76 & 83 FOR EXPLANATION OF SYMBOLS.

FIG. 77. Magnitude of frequency and inrush current when switching a capacitor.

If the capacitor is already fully charged with the opposite polarity when the switch is closed the inrush current transient will be twice the values indicated.

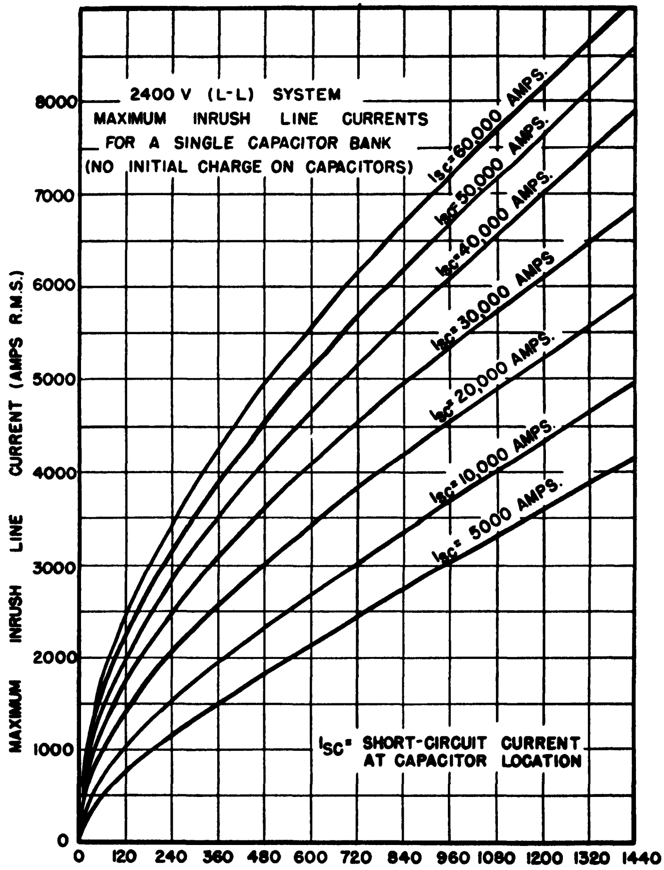


Fig. 78. Inrush currents when energizing a capacitor from a 2,400-volt circuit.

The inrush current may also be expressed in terms of circuit voltage, capacitor kvar, and line short-circuit current. Figures 78 through 82 give this information in convenient form.

FREQUENCY OF TRANSIENT INRUSH CURRENT

The classical expression for natural frequency of the inrush current transient in the circuit of Fig. 76*D* is

$$f_n = \frac{1}{2\pi\sqrt{LC}}$$

For the 60-cycle system with reactances expressed per unit this reduces to

$$f_n = \frac{60}{\sqrt{X_L/X_C}} \text{ cycles}$$

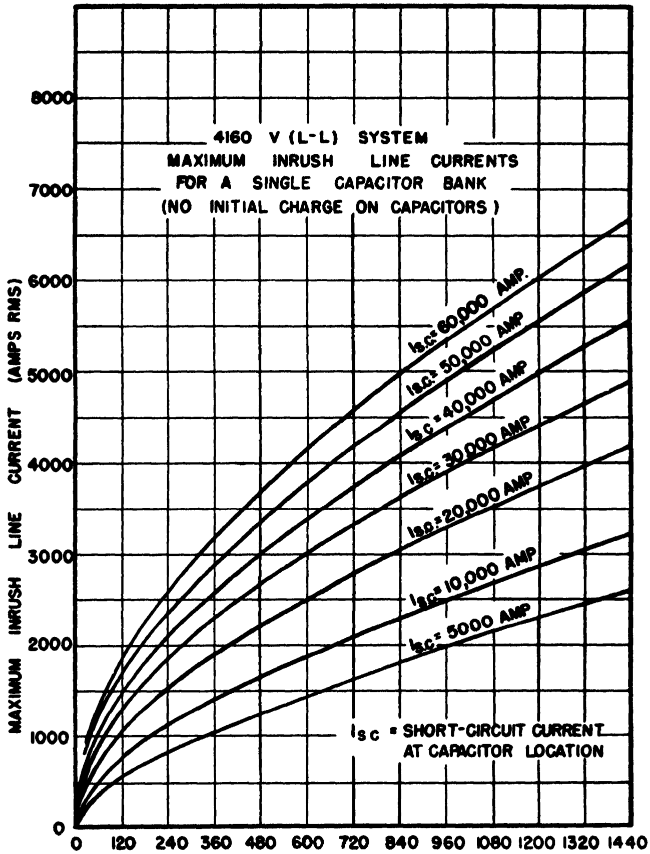


FIG. 79. Inrush currents when energizing a capacitor from a 4,160-volt circuit.

Figure 77 shows the natural frequency per cent in terms of $X_L\left(\frac{100}{X_C}\right)$.

CAPACITORS SWITCHED IN PARALLEL

When one capacitor is already energized and a second capacitor is switched on, two distinct transients occur, one due to the reactance in the source in relation to the switched capacitor and the second due to the reactance between the two capacitors in relation to the one switched. Since the second transient is by far the more important it is generally the only one to be considered.

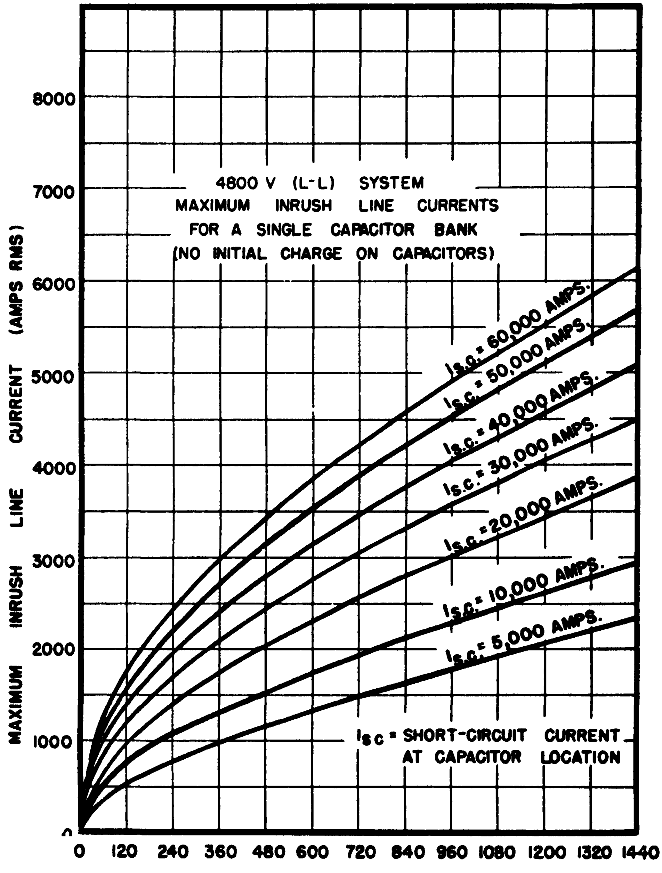


FIG. 80. Inrush current when energizing a capacitor from a 4,800-volt circuit.

Consider Fig. 83*A*, representing the case just stated,

where E = $\sqrt{2}$ × rms a-c voltage.

R_2 = source resistance.

X_{L2} = source reactance.

X_{C2} = capacitor already energized.

R = resistance of the circuit between capacitor banks.

X_L = reactance between banks.

X_{C1} = capacitor being switched on.

The reactance X_L is usually quite small compared with X_{L2}, hence a high-frequency equalizing current of large magnitude flows between X_{C2} and X_{C1}, followed later by a slower low-current transient between the complete bank and the source. The latter is usually of secondary importance and may be ignored by assuming the circuit shown in Fig.

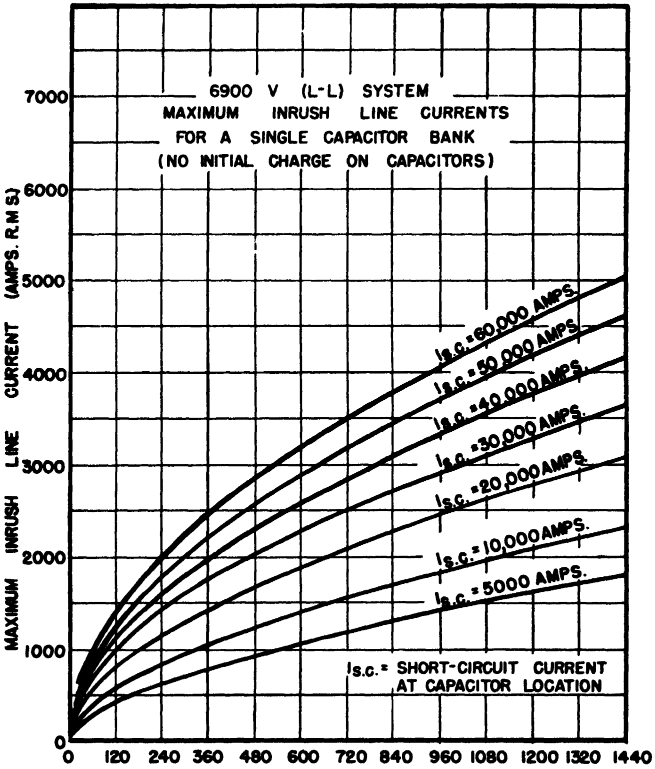


FIG. 81. Inrush current when energizing a capacitor from a 6,900-volt circuit.

83*B*. The two values of capacitor may be combined as shown in Fig. 83*C* by adding the X_C values. To do this it is necessary to express the reactance of the capacitor already energized, X_{C2}, in "per unit" on the kva base of the capacitor being added. For example, if the capacitor being added is of the same kva as the one already energized, then $X_C = 2$ per unit. If the one already energized is four times the one being added, then X_C equals 1.25 per unit.

The transient magnitude in "per unit" of the normal current of the capacitor added is given by the equation

$$I_{\text{transient}} = \frac{1}{\sqrt{X_L X_C}} \text{ per unit}$$

and the values may be read on the curve, Fig. 77, and the frequency is given by the equation

$$f_n = \frac{60}{\sqrt{X_L/X_C}} \text{ cycles}$$

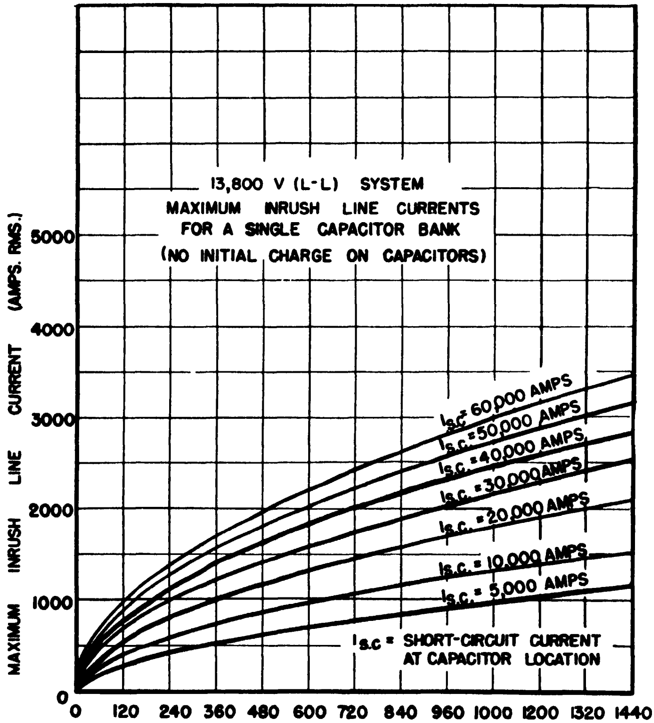


FIG. 82. Inrush current when energizing a capacitor from a 13,800-volt circuit.

The frequency may also be read on the curve, Fig. 77.

Example (five equal capacitors, four energized and one switched on):

$$X_L = 0.00031 \text{ per unit} = 0.031 \text{ per cent}$$
$$X_C = 1.25 \text{ per unit} = 125 \text{ per cent}$$

$$X_L \times \frac{X_C}{100} = 0.039$$

Referring to Fig. 77, this gives a current of 51 times the normal current for the capacitor switched on.

Consider the frequency of the oscillation

$$X_L \times \frac{100}{X_C} = 0.025$$

Referring again to Fig. 77, this gives a frequency of 3,800 cycles.

Using the same example shown in Fig. 76*D* the line to neutral values on the basis of energizing bank 2 when bank 1 is already energized are shown in Fig. 84. Taking X_{C2} as the base,

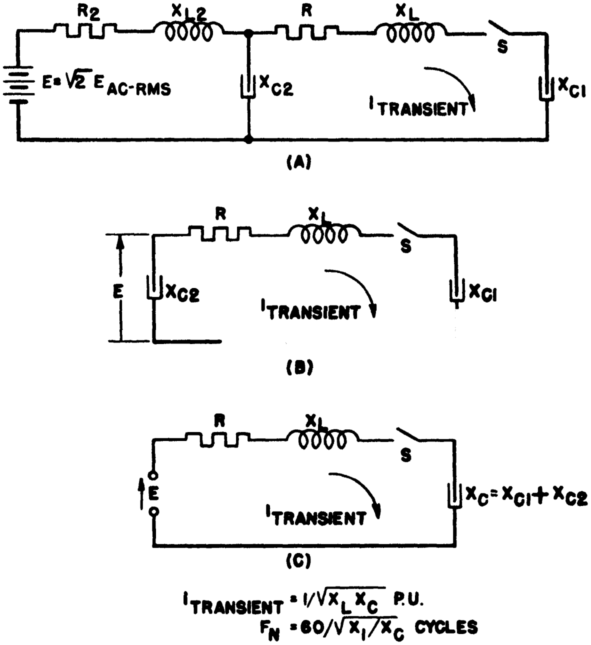


FIG. 83. Capacitors switched in parallel.

$$X_C \text{ per unit} = X_{C1} + X_{C2} = \frac{75.5 + 75.5}{75.5} = 2 \text{ per unit}$$

$$X_L \text{ per unit} = \frac{0.025}{75.5} = 0.0332 \text{ per unit}$$

$$I_{\max} = I_n \frac{1}{\sqrt{X_L X_C}} = \frac{I_n}{\sqrt{0.0332 \times 2}} = \frac{I_n}{\sqrt{0.0664}} = 38.8\ I_n$$

$$I_n = \frac{\text{kva}}{\sqrt{3}\ \text{kv}} = \frac{2{,}520}{\sqrt{3} \times 13.8} = 105.4$$

$$I_{\max} = 105.4 \times 38.8 = 4{,}100 \text{ amp rms}$$

By another method (two banks in series while the second bank is being energized),

$$C = \frac{C_1 \times C_2}{C_1 + C_2}$$

$$= \frac{35.2 \times 35.2}{35.2 + 35.2} = 17.6\ \mu\text{f}$$

$$I_{\max} = \frac{E_{Ln}}{\sqrt{L/C}} = \frac{E_{Ln}}{\sqrt{66.3/17.6}} = \frac{13{,}800}{\sqrt{3}} \times \frac{1}{1.94} = 4{,}100 \text{ amp rms}$$

To get peak first-cycle current use peak voltage (rms $\sqrt{2}$) instead of rms volts or multiply maximum rms current by $\sqrt{2}$.

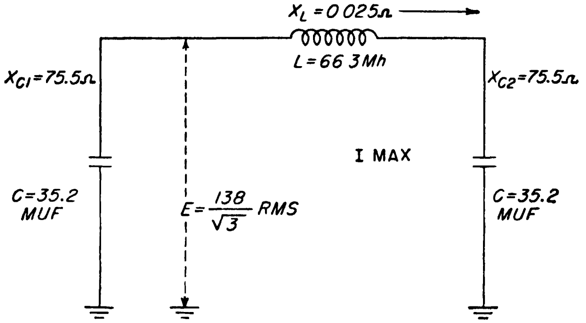


FIG. 84. Line-to-neutral values for example shown in Fig. 76D.

Unless the capacitor banks are quite large and the X_L between banks unusually small, these inrush currents do not enter into the selection of the circuit breaker. That is, a breaker which has sufficient interruption capacity to handle a system fault is usually quite capable of handling these inrush currents. This may not be true under certain conditions—for example, where many switching operations occur daily as in a capacitor equipped with relays for automatically switching the capacitor to control-system voltage. Such cases require special consideration. These inrush currents may be reduced by adding a small amount of inductance between banks.

Because of system reactance which is always present, the inrush caused by energizing one capacitor bank is usually of no consequence.

It is desirable always to allow the capacitor to discharge before reenergizing; and where automatic control is used the setting of the time-delay relays should be coordinated with the discharge means so as to prevent reenergizing a capacitor which is not substantially discharged.

DEENERGIZING TRANSIENTS

When the breaker is opened to deenergize a capacitor bank the initial voltage across the breaker is zero. A half cycle later when the line voltage has reversed, and the capacitor voltage is still the same as when the breaker started opening, the voltage across the breaker is doubled. If the breaker has already opened sufficiently or in some manner acquired sufficient insulation to withstand this double voltage, we may say that the breaker is doing a satisfactory job in deenergizing the capacitor. If, on the other hand, the breaker restrikes on this double voltage, a high oscillatory current flows. The current is high because the voltage is doubled. The current is limited, however, by the circuit reactance. This oscillatory discharge may subject both the capacitor and the circuit to high-voltage transients and for this reason restriking is undesirable in single-bank installations. Restriking of a breaker used to switch a second bank on when one bank is already energized may be more serious because of the higher magnitude of these oscillatory currents due to restriking since the reactance between banks is usually not sufficiently high to be of much help in limiting the current. Restriking in the case of parallel banks may materially increase the breaker maintenance due to contact erosion, especially on frequent switching as in the case of an automatically switched capacitor.

Experience has shown that restriking on deenergizing rarely occurs on voltages below 24 kv, and again breakers that are selected to handle the system fault current, and which are reasonably fast in operation, are quite capable of deenergizing capacitor banks on 13 kv and below. The selection of breakers should receive careful consideration where the banks are quite large and particularly where frequent switching is expected. This is even more important where the circuit voltage is above 13 kv.

LIMITING INRUSH CURRENTS

Where several large banks of capacitors are located at one point and switched separately, the inrush currents may be high due to the small amount of reactance and resistance in the circuits separating one bank of capacitors from the next. The inrush-current magnitude may be reduced by inserting resistance or inductance, or both, in these connections between capacitor banks.

The amount of resistance necessary to make any worthwhile reduction in inrush current is too large to be tolerated from the standpoint of continuous loss. It is more practical to insert a small amount of reactance either by using a reactor or by simply arranging the wires so as to have large spacing and maximum practical length. The latter practice is usually followed and, except in special cases, this limits the inrush current a sufficient amount.

Bibliography

BUTLER, J. W.: Analysis of Factors Which Influence the Application, Operation, and Design of Shunt Capacitor Equipment Switched in Large Banks, A.I.E.E. Great Lakes Dis. Meeting, Minneapolis, September 27–29, 1939.

HARDER, E. L., and V. R. PARRACK: The 13,500 KVAR Capacitor Installation at Newport News, A.I.E.E. Southeastern Meeting, Roanoke, Va., November 16, 1943.

SCHROEDER, T. W.: The Cause and Control of Some Types of Switching Surges, *A.I.E.E. Trans.*, vol. 62, November, 1943.

SCHROEDER, T. W., E. W. BOEHNE, and J. W. BUTLER: Tests and Analysis of Circuit Breaker Performance When Switching Large Capacitor Banks, A.I.E.E. Summer Meeting, Chicago, June 22–26, 1942.

CHAPTER 7

AUTOMATIC CONTROL OF CAPACITOR KVAR

NEED FOR AUTOMATIC CONTROL

It is sometimes necessary or desirable to switch capacitors on and off automatically in industrial plants to avoid overvoltage conditions during periods of light load. This is more likely to be the case where plants are near the ends of long lines, and where very wide fluctuations in load occur. The test for the need for switching the capacitor off is to calculate the light-load voltage with the capacitor connected. By this means it is possible to determine in advance whether it is practical to plan to leave the capacitor on continuously. The method of determining the voltage boost that will be produced by the capacitor has already been discussed in Chaps. 4 and 5. Whether the capacitor is to be switched off and on manually or automatically depends entirely on local conditions, location of the capacitor, availability and dependability of an attendant, etc.

If the capacitor is to be switched on and off automatically, it is usually done because of the boost in voltage caused by the capacitor and the resulting final voltage when this boost is added to the normal voltage during periods of light load on the plant. Capacitors are therefore generally switched in relation to circuit voltage. In some large industrial plants special conditions warrant switching of the capacitor according to the load power factor. In this case kvar of the load is used as a reference. Sometimes load-current reference can be used to determine the switching.

In the case of distribution systems the switching of the capacitor may be desirable merely to avoid overvoltage during light loads, but more often the switching operation becomes a means of voltage regulation.

The effectiveness of shunt capacitors can often be increased by switching a portion of the banks on and off as needed. By so doing two things can be accomplished:

1. Kvar can be supplied as needed during peak load conditions without the risk of excessive voltage rise during light-load conditions.

2. The voltage level on the system can be regulated by making use of the boost that can thus be produced with capacitors when the voltage level might otherwise fall below desired levels.

METHODS OF CONTROL

In general the capacitors may be switched off when the voltage is high and on when the voltage is low. They may be switched primarily to control voltage or they may be switched when needed to compensate for load reactive, using the voltage as an indicator of the need for the capacitors.

If the system voltage is controlled by a voltage regulator near the capacitor, voltage will no longer serve as a reliable indicator of the need for supplying kvar at this point on the system. If the intention is to vary the capacitor kvar to suit the local kvar requirements, it is necessary to resort to other means for bringing about the switching operation. There are two ways of doing this, switch according to load current or switch according to load kvar.

If the load voltage is maintained relatively constant due to the use of voltage regulators and if the power factor remains relatively constant during wide variations in load, it is practical to use load-current variations to bring about the switching of the capacitor. This is obvious since it may then be assumed that the need for capacitors varies in proportion to load current.

If the load power factor varies and voltage is being regulated by other means, it is desirable to use kvar variations in load to initiate the switching operations.

Whether switched by voltage, current, or kvar, the equipment consists of

1. A response relay sensitive to voltage, current, or kvar.
2. Suitable time-delay relays and auxiliaries to avoid too-frequent switching in response to minor load fluctuations.
3. An electrically operated switch.
4. If the capacitor is switched in steps suitable relays are used to produce the step-by-step switching in either direction, each step setting up the circuit for the next step.

SWITCHING IN STEPS

When switching by voltage or kvar, the capacitor may be made up of several steps because the initiating relay is influenced by the addition or subtraction of capacitor kvar, and the addition or removal of further steps is governed by the results of the step just completed.

When switching by current, there can be only one step under control of a single current relay. If several steps are used for current control, each step is controlled by its own current relay.

The need for switching the capacitor in steps and the number of steps are governed by the size of the capacitor relative to the circuit and load, and the total effect of the capacitor.

If the voltage relay is set to put the capacitor on when the voltage drops 2 per cent and remove it when the voltage rises 2 per cent with respect to a mean value, we have a total spread of 4 per cent. The voltage produced by the capacitor should not be greater than half this spread. In this case, therefore, the maximum change that should be produced by the capacitor is 2 per cent. If the capacitor being considered will only produce a 2 per cent change on the circuit, then the capacitor may be switched in one step. If the capacitor is capable of producing a 6 per cent change it should be switched in three steps.

When switching on the kvar basis the number of steps is arrived at in a similar manner. The spread of the relay setting desired and the size of the capacitor determines the number of steps into which it will be divided.

Where the capacitor is switched by current it is usually switched in one step. The size of the capacitor is chosen to meet the requirements for the particular load with which it is used, and the capacitor is switched off when this load drops to a point below which it is no longer needed.

DETERMINATION OF THE TYPE OF CONTROL REQUIRED

The decision as to type of control depends upon the benefits to be expected, the size of the capacitor installation, the variations of voltage with load, and the extent to which the kw and kvar load varies over a typical load period.

Measurements of kw, kvar, and voltage over a typical load period will determine

1. Total capacitor kvar required under maximum load conditions.
2. Total capacitor kvar required at light load.
3. Total capacitor kvar to be switched.
4. Maximum capacitor kvar to be switched at any one time.
5. Ratio of total kvar to be switched to the maximum kvar to be switched at one time.

The first two requirements have already been discussed in Chaps. 4 and 5 and will not be discussed here. The total capacitor kvar to be switched off is determined by the boost in voltage, or the change in voltage caused by the capacitor, or—in the case where the power factor is to be controlled by switching in respect to kvar of the load—the total capacitor kvar to be switched is governed by the degree of change in the kvar of the load.

The maximum capacitor kvar that can be switched at one switching operation is dependent on the total change that will be produced when the total amount is switched. For example if the total amount to be switched (1, above) will produce a 6-volt change and the maximum change that can be tolerated on one switching operation is 2 volts, then three steps will be required.

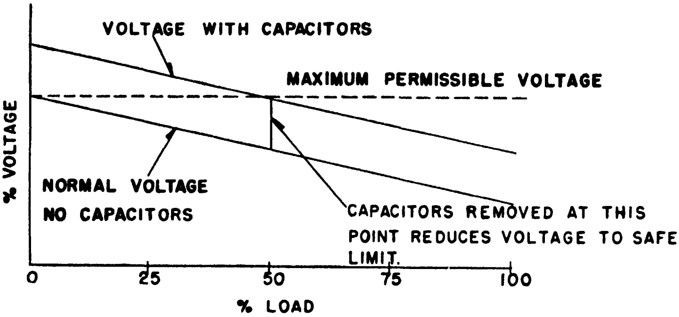


FIG. 85. Graphic illustration of voltage regulation by means of automatic capacitors switching in response to changes in voltage.

After a study of conditions and the effect of the various types of control have been considered, a decision may be made on the type of control to be applied.

SWITCHING IN RESPONSE TO VOLTAGE

Automatic switching of capacitors in response to voltage changes is applied where

1. Objectionable voltage variation occurs with varying loads.
2. No other voltage regulating means are employed.

While capacitors are installed primarily for power-factor improvement, they do cause a voltage rise over that voltage which would exist if the capacitor where not connected. The voltage rise caused by the leading current drawn by the capacitor flowing through the system reactance cancels or nearly cancels the voltage drop caused by the lagging component of the full-load current flowing through the same system reactance. With light loads the lagging current drawn by the load is reduced, while the capacitor leading current remains constant. This causes a rise in voltage at no load or light load. The rise is illustrated graphically in Fig. 85.

If the load voltage before adding capacitors is near the upper permissible limit, the capacitor must be removed to keep the voltage within satisfactory limits. If the voltage regulation with load is excessive at intermediate loads, then it may be necessary to remove capacitors in several steps (see Fig. 86).

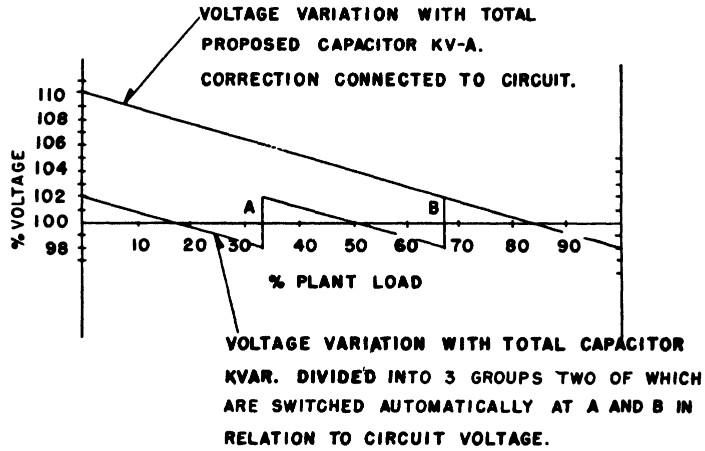


FIG. 86. The effect of multistep switching.

In determining the amount of kvar to be switched and the amount to be connected permanently,

1. Determine light-load voltage with proposed capacitor connected.
2. If the light-load voltage (1) is objectionable, then determine the maximum capacitor kvar permissible during light-load conditions that does not exceed the upper voltage limit.
3. Determine maximum capacitor kvar that can be switched and stay within satisfactory voltage limits.
4. The difference between the total capacitor kvar proposed (1) and the capacitor kvar permissible during light-load conditions (2) determines the total capacitor kvar to be switched.
5. The ratio of total capacitor kvar to be switched (4) to the maximum capacitor kvar that can be switched and stay within satisfactory voltage limits (3) determines the minimum number of switching steps.

Example: Assume the case of a load at the end of a long feeder where an objectionable voltage drop occurs between the regulated bus and the load and it is desired to keep the voltage within ±2.5 per cent of normal.

If sufficient capacitor correction is installed to raise the voltage at the load to a desirable value during full load, the voltage at light load is found to be 10 per cent high. In order to keep within the desired ±2.5 per cent, the size of capacitor steps should be selected to give a voltage change of 5 per cent minus a margin or tolerance which will prevent the possibility of hunting.

If it is decided to use a 0.5 per cent margin at each extreme, then the capacitor step should change the voltage 4 per cent.

The best arrangement in this case would be to have a permanently connected capacitor to give a voltage rise of about 2 per cent and two steps of switched capacitor, each to give a voltage change of 4 per cent, the first step to be switched at approximately 33 per cent load and the second step at 66 per cent load.

The decision in this case should definitely be to switch the capacitor in two steps automatically in response to circuit voltage at the load.

SWITCHING IN RESPONSE TO LOAD CURRENT

Current control is used for switching on applications where the voltage is well regulated and the power factor of the load remains substantially constant with variation in kw loading; or if the power factor of the circuit varies in definite order with variation in kw loading. Current control is practiced only for single-step switching; however, more than one capacitor with its switch and single-step control may be used at the same location to obtain the equivalent of multistep control. The current transformer for energizing the current relay should always be placed in the circuit on the load side of the capacitor to avoid changing the value of current flowing to the relay when the capacitor is switched.

SWITCHING IN RELATION TO LOAD KVAR

When capacitors are connected to a well-regulated bus, the voltage regulator will usually keep the voltage within satisfactory limits independent of the amount of capacitor kvar applied. In such a case, control in response to line voltage can be disregarded and consideration given to the other methods to determine from which the greater benefits can be derived.

If sufficient capacitor kvar is to be added to correct for full-load conditions, it may be desirable to switch the capacitors with the variations in load to obtain the maximum benefits by keeping the demand and losses at a minimum, or to avoid the penalty of excessive leading power factor during light-load periods. Under such conditions, either kvar or current control have their separate field of application. If both control methods are applicable the existing physical arrangements of the circuits may dictate the type of control to be selected.

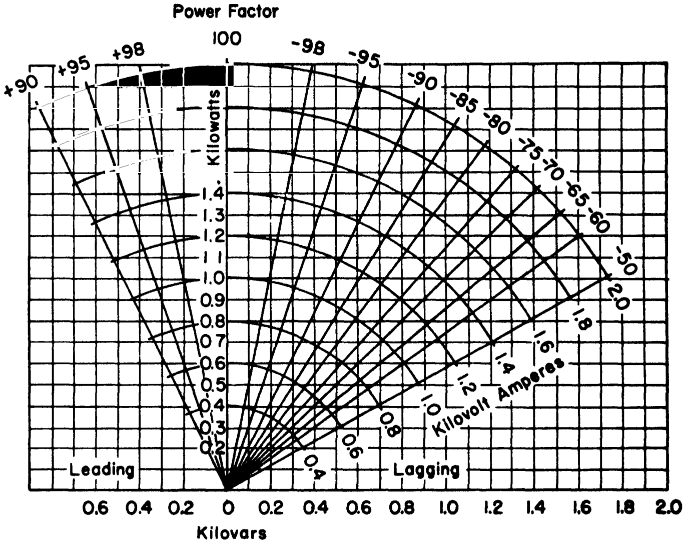


FIG. 87. Relation between kvar, kw, kva, and power factor.

On those applications where load voltage is well regulated but power factor varies considerably with kilowatt loading, consideration should be given to switching the capacitor in response to the kvar load.

Example: It is decided to apply sufficient capacity to improve power factor at full load from 70 to 96.5 per cent to reduce the kva demand to approximately 79 per cent of its original value.

From the chart in Fig. 87 it is determined that with a full load being represented by 1 kw at 70 per cent power factor, 0.75 kvar is required to improve the power factor to 96.5 per cent.

If we make the further assumptions that the load varies between 0.2 and 1.0 kw and the uncorrected load power factor varies between 65 and 79 per cent lagging and it is desired to keep the power factor variation within 90 per cent lagging and leading, then the maximum total capacitor kvar permitted at light load can be determined.

The maximum capacitor kvar permitted at light load is the kvar at

0.2 kw and 90 per cent power factor plus the kvar at 0.2 kw and 79 per cent power factor or (0.096 + 0.154) 0.25 kvar. With 0.25 kvar capacitor permanently connected the maximum capacitor kvar switched in one operation can be determined.

Note that the horizontal distance of 0.25 kvar between the 65 and 90 per cent power factor lines occurs at 0.362 kw. The horizontal distance between the 90 per cent power factor line and the vertical zero line at this point is 0.174 kvar.

The 0.174 kvar plus 0.094 kvar, the leading reactive permitted at 0.2 kw without exceeding 90 per cent power factor leading, is 0.268 kvar, the maximum size capacitor to be switched in one operation. Since the microfarad tolerances are in the plus direction and the capacitor kvar varies as the square of the voltage for a given rating, the relay should always be adjusted for a spread greater than the kvar capacitor rating by a tolerance which will prevent hunting. If the relay setting is to be adjusted for a spread of 0.268 kvar, the capacitor kvar rating should be approximately 75 per cent of the relay setting or (0.268 × 0.75) = 0.2 kvar. The number of capacitor switching steps is therefore (0.75 − 0.25)/0.2 = 2.5. The 0.75-kvar capacitor should therefore be divided into four groups: one 0.25-kvar capacitor to be permanently connected and three 0.166-kvar capacitor, to be switched automatically and selectively in response to kvar.

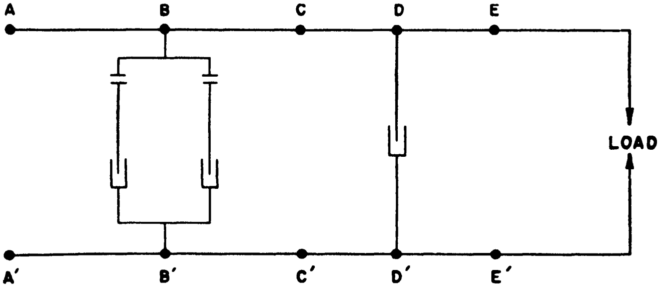


FIG. 88. Analysis of circuit load points.

ANALYZING CIRCUIT CONDITIONS

In analyzing circuit conditions for the application of automatically switched capacitors, there are always two power factors involved and in some instances more. To illustrate how some of the various circuit conditions should be analyzed, a diagram, Fig. 88, and a tabulation, Table 19, are shown. The values shown in the tabulation are based on the following assumptions:

1. The power factor at point *E-E′* remains at 70 per cent lagging for the maximum load variation of 25 to 100 per cent.
2. Capacitor of 0.25 kvar at point *D-D′* to improve the power factor or unity at minimum load of 25 per cent.
3. Add two 0.25-kvar capacitors at point *B-B′* to improve the circuit power factor to 97 per cent lagging at full load; one capacitor to be switched on at 50 per cent kilowatt load and off at 40 per cent kilowatt load, and the second capacitor to be switched on at 75 per cent kilowatt load and off at 65 per cent kilowatt load.

It will be noted by referring to point *A-A′* (Fig. 88 and Table 19) that at 25 per cent load and with 0.25 kva of capacitance at *D-D′* the power factor is unity. As the load is increased to 50 per cent the power factor goes to 88.9 per cent lagging, and when a 0.25-kva capacitor is added at this point the power factor is improved to 99.9 per cent lagging. As the load increases from 50 to 75 per cent the power factor drops to 94 per cent lagging. At this point the addition of 0.25 kva of capacitance brings it to unity again. As the load further increases to 100 per cent the power factor drops to 96.5 per cent lagging.

Now if the load drops from 100 to 65 per cent the power factor rises to unity, then over to slightly leading at 98.9 per cent; and if at this point a 0.25-kva capacitor is removed it goes to 97.2 per cent lagging. Further reduction of load to 40 per cent results in a leading power factor of 97.2 per cent, which changes to 93.3 per cent lagging if a second 0.25-kva capacitor is removed. A further reduction of load to 25 per cent results in a power factor of unity, as in the beginning.

It should be noted that the capacitors could be switched from a current-sensitive relay energized from a current transformer inserted in the circuit between *B* and *C* or between *D* and *E*. The kva values listed in column 8, Table 19, should be used in selecting the current relay settings if the current transformer is located between *B* and *C*. If the current transformer is located between *D* and *E*, the kva values listed in column 6, Table 19, should be used in selecting the current relay settings.

COMPONENTS OF AUTOMATIC-CONTROLLED CAPACITORS

The capacitor may be any type of indoor or outdoor shunt capacitor with or without provisions for housing the control. Usually the capacitor is equipped with a switch assembled within the same housing; however, the switch may be separately mounted. The switch must be electrically operated. Electrically operated switches may be of the type that must be continuously energized, as in the case of a contactor,

TABLE 19. ANALYSIS OF CIRCUIT CONDITIONS FOR THE APPLICATION OF CAPACITORS (See Fig. 85)

Load kw	Capacitor kva		Conditions at *E-E'*			Conditions at *C-C''*			Conditions at *A-A'*					
									Load increasing			Load decreasing		
	B-B'	*D-D'*	Power factor*	Kva	Kvar	Power factor	Kva	Kvar	Power factor	Kva	Kvar	Power factor	Kva	Kvar
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)
1 0	0 50	0 25	0 70	1 43	1 02	0 80	1 25	0 75	0 965*	1 035	0 27*	0 965*	1 035	0 27*
0 9	0 50	0 25	0 70	1 285	0 908	0 81	1 11	0 65	0 984*	0 915	0 158*	0 984*	0 915	0 158*
0 8	0 50	0 25	0 70	1 14	0 807	0 824	0 972	0 55	0 997*	0 803	0 057*	0 997*	0 803	0 057*
0 75	0 50	0 25	0 70	1 07	0 757	0 832	0 902	0 50	1 00	0 75	0 007	1 00	0 75	0 007
0 75	0 25	0 25	0 70	1 07	0 757	0 832	0 902	0 50	0 94*	0 798	0 27*			
0 7	0 50	0 25	0 70	1 0	0 706	0 84	0 833	0 45				0 998†	0 702	0 44†
0 7	0 25	0 25	0 70	1 0	0 706	0 84	0 833	0 45	0 958*	0 732	0 206*			
0 65	0 50	0 25	0 70	0 93	0 656	0 85	0 767	0 50				0 989†	0 657	0 094†
0 65	0 25	0 25	0 70	0 93	0 656	0 85	0 767	0 40	0 972*	0 668	0 156*	0 972*	0 668	0 156*
0 6	0 25	0 25	0 70	0 857	0 605	0 863	0 696	0 35	0 984*	0 61	0 105*	0 984*	0 61	0 105*
0 5	0 25	0 25	0 70	0 715	0 505	0 893	0 56	0 25	0 999*	0 50	0 005	0 999*	0 50	0 005
0 5	0	0 25	0 70	0 715	0 505	0 893	0 56	0 25	0 889*	0 563	0 255*			
0 45	0 25	0 25	0 70	0 643	0 454	0 913	0 494	0 20				0 994†	0 453	0 046†
0 45	0	0 25	0 70	0 643	0 454	0 913	0 494	0 20	0 91*	0 494	0 204*			
0 4	0 25	0 25	0 70	0 572	0 404	0 935	0 428	0 15				0 972†	0 412	0 096†
0 4	0	0 25	0 70	0 572	0 404	0 935	0 428	0 15	0 933*	0 428	0 154*	0 933*	0 428	0 154*
0 3	0	0 25	0 70	0 428	0 303	0 986	0 304	0 05	0 984*	0 305	0 053*	0 984*	0 305	0 053*
0 25	0	0 25	0 70	0 357	0 252	1 00	0 25	0	1 00	0 25	0 002	1 00*	0 25	0 002

* Lagging power factor † Leading power factor

or they may be the conventional type of electrically operated oil or air circuit breaker. The control-circuit details, of course, vary in these two cases.

The switch must meet the requirements as to interrupting rating and continuous-current rating and must be capable of handling the inrush currents associated with frequent energizing of the capacitor. The wear of the contacts will be governed by the number of switching operations and the inrush current. The inrush current will be greater when several banks are switched in sequence, all connected at the same point on the circuit, than when a single capacitor is switched on and off of the circuit.

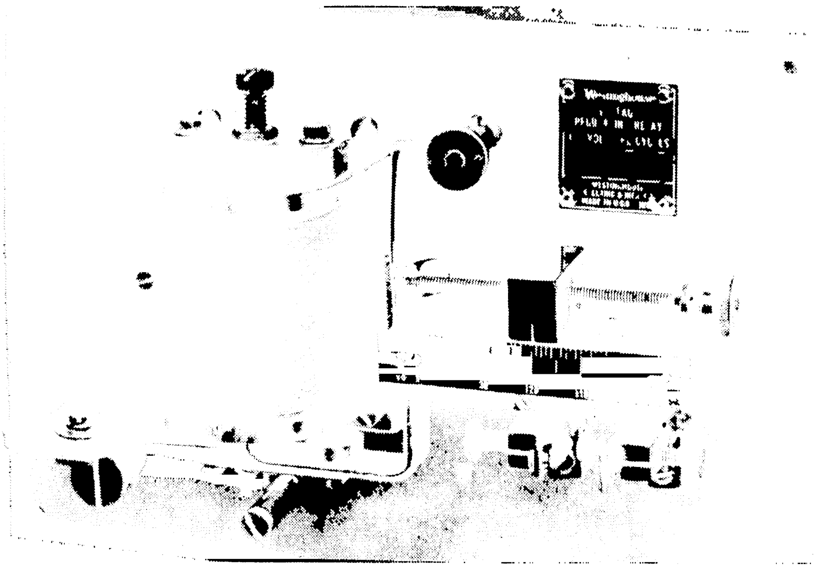


FIG. 89. Voltage-sensitive relay.

The voltage-sensitive relay, shown in Fig. 89, is an a-c solenoid type with operating parts combined into one moving element which is mounted by a square shaft resting on edge in a grooved bracket. With sufficient change in voltage, the armature of the relay will move up or down and close either the left-hand or right-hand set of contacts. The value of voltage it is desired to maintain is set by moving the balance weight with the thumb nut. The compounding is accomplished by means of a permanent magnet acting on a soft-iron armature attached to the moving element. The action of the magnet is to hold the relay element in a neutral position until sufficient change in voltage takes place to overcome this magnetic pull. When the moving element breaks away from the magnet pull, a positive contact is made. This voltage-sensitive relay is adjustable over a range of 90 to 110 per cent of a 115-volt base, and it has a standard adjustable band width of 3 to 7.5 per cent.

This type of voltage relay has been used extensively in automatically switched capacitors. It is similar to the relay that has been used for many years on voltage regulators.

FIG. 90. Kvar relay, front view.

Where the control bears a relation to load current, the current-sensitive relay may be of the same general construction as the voltage-sensitive relay previously described. A relay transformer is used to obtain a wide range of current settings. The relay can be adjusted to close its contacts to initiate the closing or opening of the capacitor switch at predetermined values of line current by selecting the proper relay transformer ratio and adjusting the balance on the moving element. The current-sensitive relay may be made adjustable over a range of 25 to 100 per cent of the coil rating of 5 amp.

A kvar-sensitive relay of a type that has been used quite extensively is shown in Figs. 90 and 91. This is an a-c solenoid type with operating parts combined into one moving element which is mounted on a hinged spring bearing. With sufficient change in kvar, the lever will rotate to close either the upper or lower set of contacts. Each coil has three windings consisting of a voltage winding and two current windings. The current windings on each coil are connected so that they magnetically oppose each other but when combined with the voltage winding and energized at a phase angle of 90 deg between the current and voltage, there is no torque developed. If the phase angle between current and voltage is shifted in the lagging direction, this results in a torque to rotate the lever in a counterclockwise direction; and if the phase angle is shifted in the leading direction, the rotation of the lever is in a clockwise direction.

Weights are suspended from the adjustable brackets at the ends of the moving lever. The rotation of the lever in a counterclockwise direction a certain distance engages the suspended weight holder on the right to restrain its movement, and rotation of the lever in a clockwise direction a certain distance engages the suspended weight holder on the left to restrain its movement. The movement of the weight holder and its weights requires a torque proportional to the weight. Since the weights are not suspended from the moving lever, it is possible to adjust the pickup of the upper or lower contacts independently of each other by varying the weights that affect the particular contacts involved. Weights may also be added to the right of the pivot center of the lever arm to have both the upper and lower contacts close in the lagging quadrant. Permanent magnets are located above the moving lever near each end to obtain quick make and break of the relay contacts.

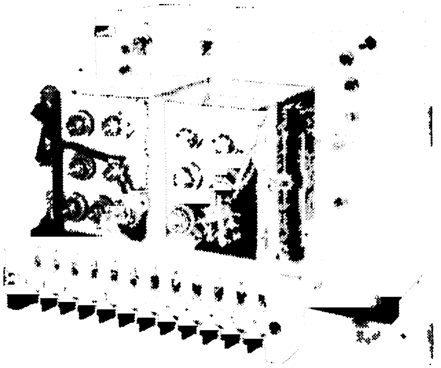


FIG. 91. Kvar relay, rear view.

The current windings of each coil have a burden of approximately 10 va at 4 amp and the voltage winding of each coil has a burden of approximately 10 va at 115 volts, 60 cycles. If the current coils are connected in series and the potential coils are connected in parallel, as is the usual case, then the total burden is approximately 20 va for the current windings and 20 va for the potential windings.

This kvar relay will provide maximum range of adjustment when used with current transformers having a rating of 125 per cent of maximum load with voltage transformers to provide nominally 115 volts for the potential coil.

In order to avoid too frequent switching of the capacitor or switching in response to minor changes it is necessary to use a time-delay device to prevent a switching operation until the conditions have remained changed for a predetermined time. A type of thermal relay that has been used for this purpose is shown in Fig. 92, with the cover removed to show the contacts. This is a two-element device. One element controls the delay in connecting the capacitor to the circuit and the other introduces the delay in disconnecting the capacitor bank. Combining the two functions in one relay makes it impossible for the capacitor to go on and off at the same time due to failure of the relays to reset.

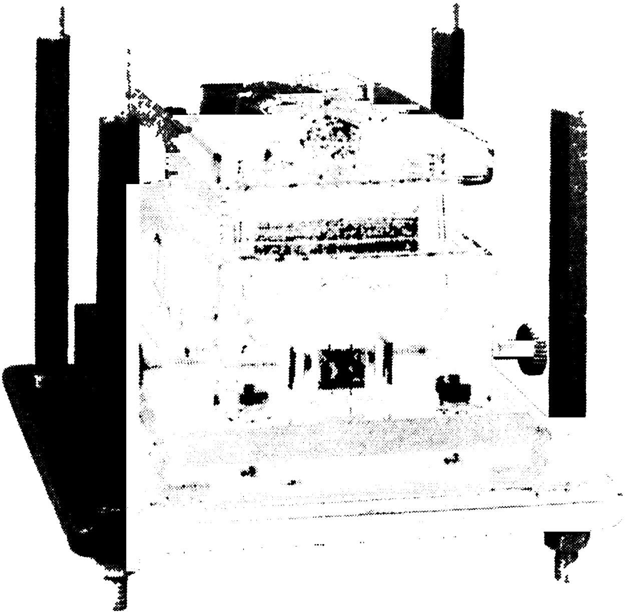


FIG. 92. Time-delay relay.

The two element relay shown in Fig. 92 consists of two bimetal elements with contacts on movable ends and two adjustable stationary contacts. The relay is assembled in a case with connections brought out to terminal studs at the rear. The secondary of one transformer is connected to one bimetal element and the secondary of the other is connected to the other bimetal element. The normal position of the moving contacts is midway between the two outside stationary contacts when the relay is unenergized. Connections are made to the end of the bimetal from which it is supported rigidly to the base. Circulating current in the bimetal element increases its temperature and causes it to move outward to make contact with the stationary contact. The time to close the contact can be varied by adjusting the position of the stationary contact with a thumb screw. The movable ends of the two bimetal elements are tied together with an insulating member, which acts to compensate for variations in ambient temperature and permits only one contact to be closed at a time.

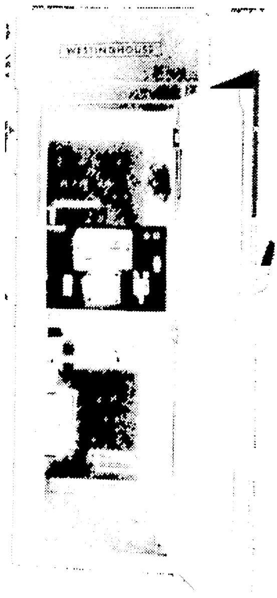


FIG. 93. Large automatic-controlled capacitor.

TYPICAL CAPACITOR EQUIPMENT WITH AUTOMATIC CONTROL

Many large capacitor assemblies in the voltage class from 460 to 13,800 volts are equipped with automatic control and electrically operated oil or air breakers. Figure 93 shows the front of such a capacitor, with the voltage relay and time-delay relays mounted on a swinging panel.

Figure 94 shows a separately mounted control operating in conjunction with a contactor to control a bank of capacitors mounted in the ceiling of an industrial plant. Installations of this kind are quite common and permit installing all the capacitors necessary to get ideal conditions under peak load with no risk of overvoltage during light load.

Figures 95 and 96 show one type of automatic capacitor that is used quite frequently on distribution lines. This is a 180-kva 2,400/4,160-volt capacitor consisting of twelve capacitor units, an oil-immersed contactor, voltage relay, time-delay relays, fuses, potential transformer, and capacitor-unit fuses, all assembled into a single housing for mounting on pole crossarms.

Sometimes it is desirable simply to add an automatic control and oil contactor to a conventional bank of crossarm-mounted capacitors. In this case an automatic control as shown in Fig. 97 has often been used.

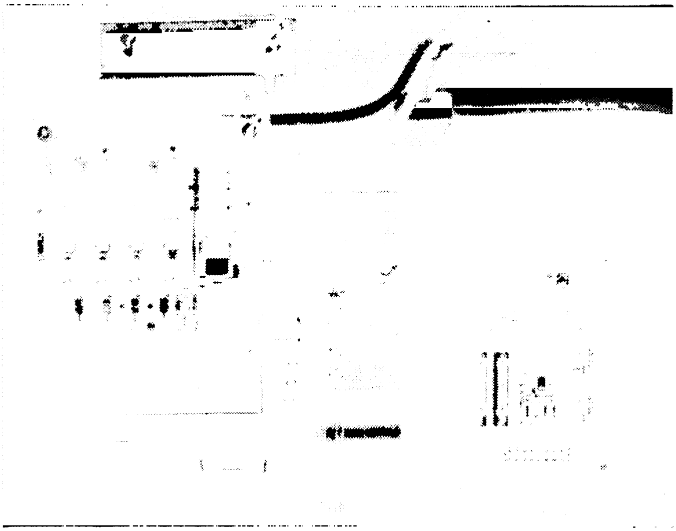


FIG. 94. Low-voltage automatic capacitor.

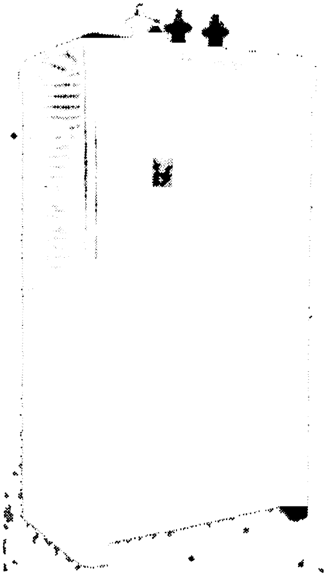


FIG. 95. Pole-housed automatic capacitor, closed.

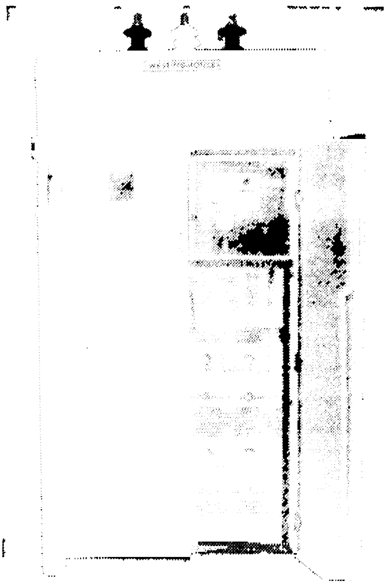


FIG. 96. Pole-housed automatic capacitor, open.

Figure 98 shows this control with cover removed, and Fig. 99 shows the rear view of the panel.

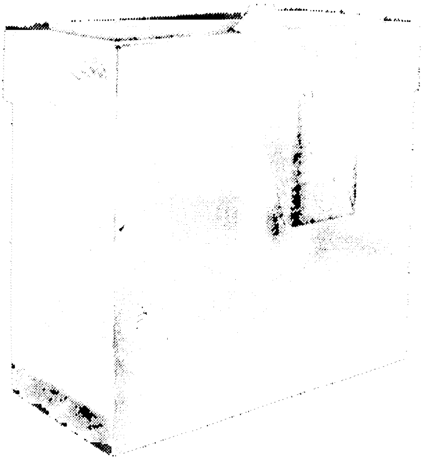


Fig. 97. Automatic control device for one-step control, outdoor, separately mounted.

Fig. 98. One-step control with cover removed to show voltage relay.

Figure 100 shows a typical oil-immersed contactor for use in switching a pole-mounted 180-kvar capacitor for 2,400 or 4,160 volts.

Figure 101 shows a complete installation with contactor (Fig. 100) mounted above the capacitors and the control (Fig. 97) mounted on the pole near the ground.

Figures 102, 103, and 105 show the way in which the various types of automatic control are connected to the circuit. Figure 104 shows a typical diagram of a three-step kvar control with rectox solenoid-operated air circuit breakers.

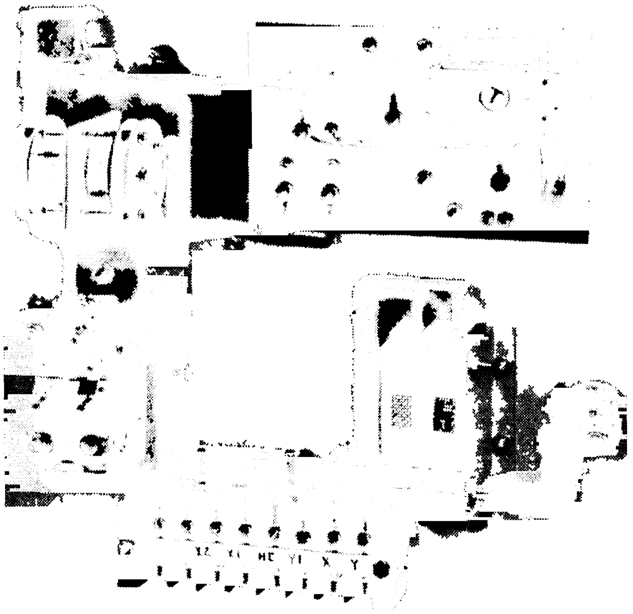


Fig. 99. Rear view of control-unit panel.

GENERAL APPLICATION DATA

Capacitors may be switched to avoid overvoltage on lamps, motors, and other equipment during light load, and to keep within the voltage operating limits of standard capacitors.

Capacitors may be switched on distribution circuits or plant feeders beyond the voltage regulators to improve voltage regulation by reducing the current flowing in the feeders. This voltage regulation is accomplished without changing existing regulating equipment and lowers the IX and IR losses in the circuit.

Capacitors may be switched to keep the power factor of a load within certain limits and thus reduce power costs where power is purchased under a rate schedule which includes power factor.

In some few cases harmonics are objectionable at light load. Capacitors draw excessive current when there are harmonics present. Automatically switching the capacitor off if it is not needed is a simple solution and less expensive than adding equipment to filter out the harmonics or block their current flow through the capacitor

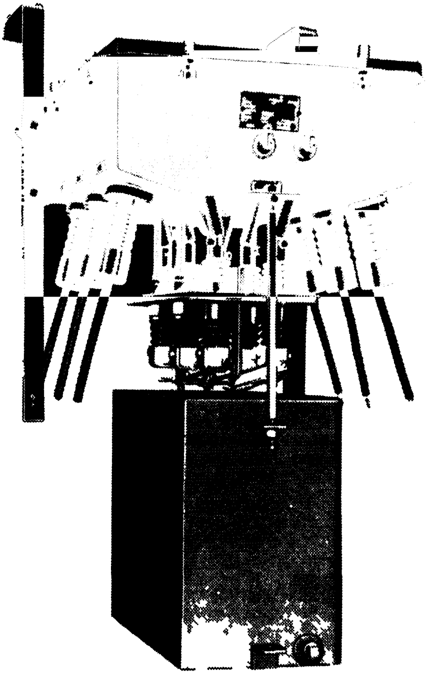


Fig 100 Three-pole 20-amp, 7,500-volt oil switch, for crossarm mounting (*South Bend Current Controller Co, Type CP-3-20*)

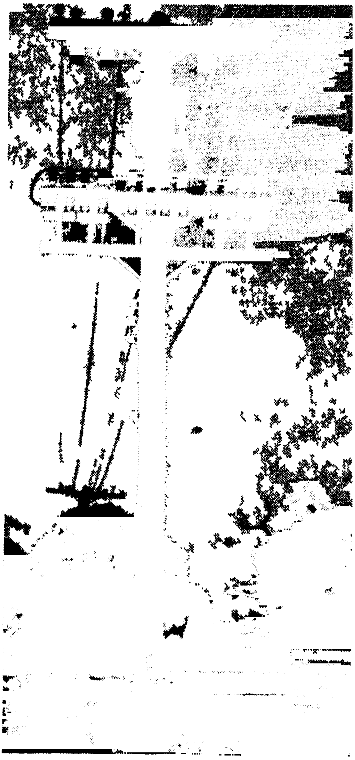


Fig 101 Typical installation showing outdoor capacitor units on the crossarm, with oil contactor above and automatic control (Fig 97) mounted below near the ground

The capacitors may be connected directly to the motor terminals so that when certain motors are shut down this amount of capacitor kvar will be disconnected from the circuit This provides an inexpensive and practical way to avoid excess capacitor kvar during light loads. Care must be exercised to avoid overcorrecting the power factor of individual motors. This was discussed in Chap. 4.

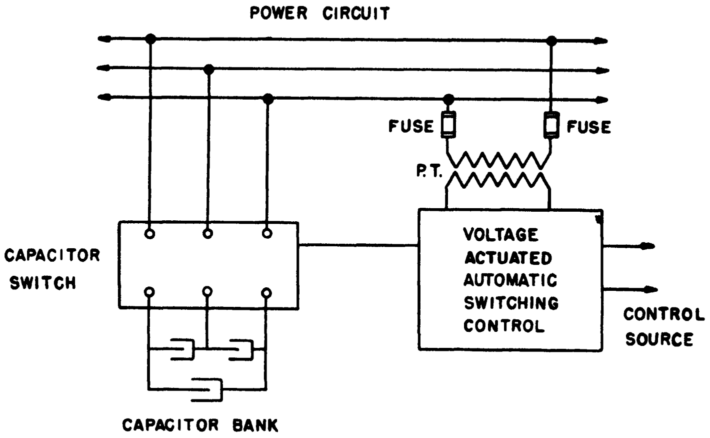


FIG. 102. Diagram showing one-step voltage control.

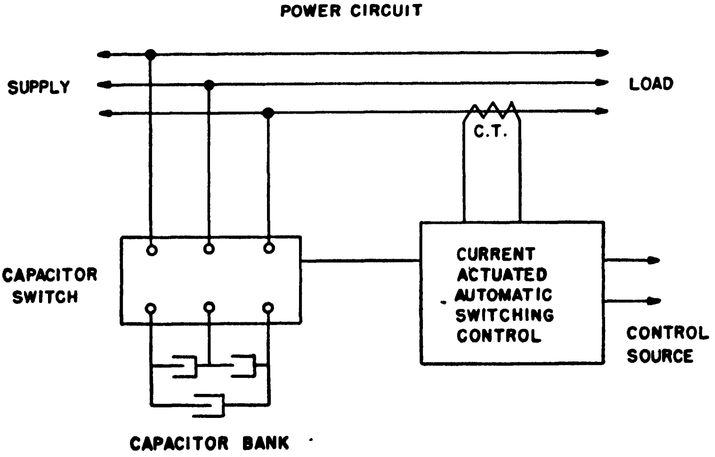


FIG. 103. Diagram showing one-step current control.

Instead of disconnecting and connecting the capacitor from the circuit the voltage on the capacitor may be reduced by means of a voltage regulator. The kvar of the capacitor drops as the square of the voltage. Reducing the voltage to 50 per cent reduces the capacitor kvar to 25 per cent. The voltage regulator can be controlled by any

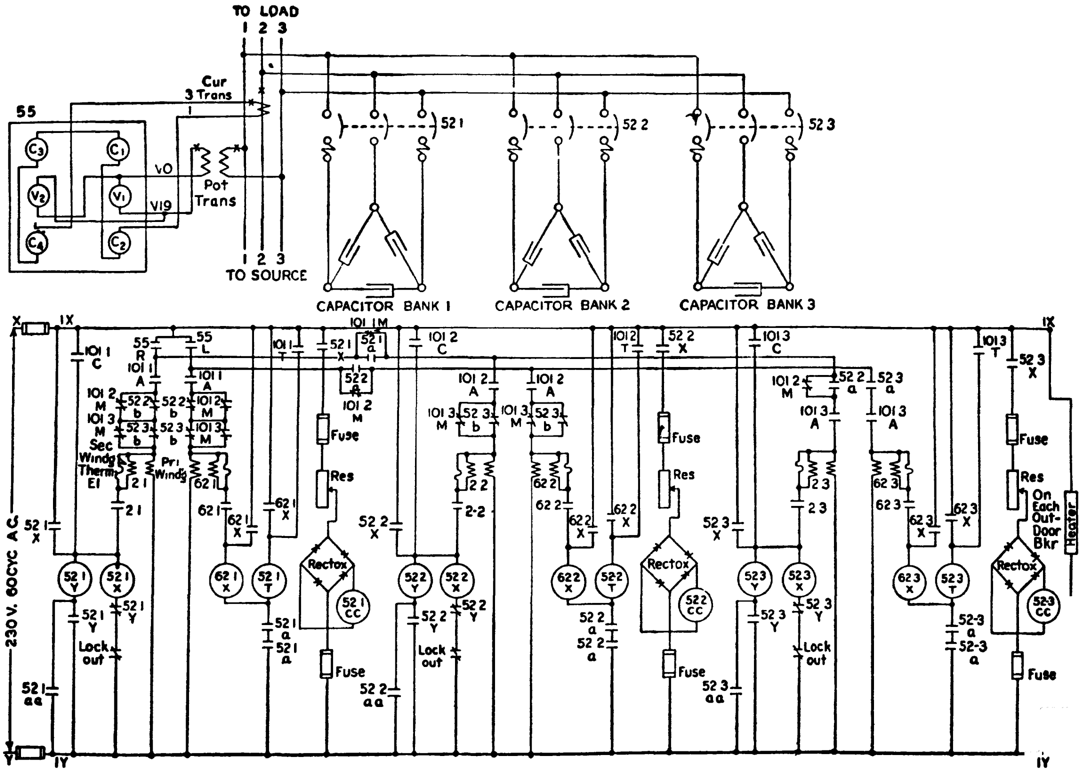


Fig. 104. Diagram showing three-step kvar control.

means desired. This type of control of capacitor kvar is seldom used due to the higher first cost, losses in the regulator, and the fact that there is rarely any need for such fine control of capacitor kvar. One, two, or three steps are usually enough. Most controls are one- and two-step.

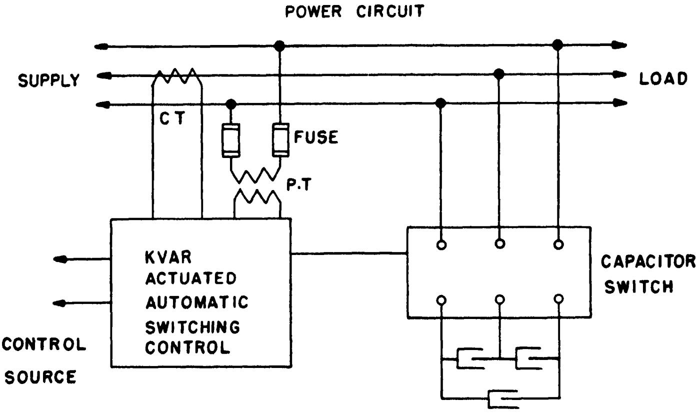


FIG. 105. Diagram showing one-step kvar control.

Bibliography

BERNICK, F., and H. S. WOODS: Automatically Operated Capacitor Equipment for Power Factor Correction, *Gen. Elec. Rev.*, vol. 35, pp. 381–383, July, 1932.

BUTLER, J. W., and E. B. POPE: Why Not Switch Capacitors with the Load? *Gen. Elec. Rev.*, vol. 41, pp. 366–369, August, 1938.

CUTTINO, W. H.: Automatic Switching Schemes for Capacitors, *A.I.E.E. Trans.*, vol. 66, 1947.

CUTTINO, W. H.: Extending the Use of Shunt Capacitors by Means of Automatic Switching, A.I.E.E. Summer Meeting, St. Louis, June 26–30, 1944.

CUTTINO, W. H., and J. E. HOBSON: Automatic Switching Multiplies Capacitor Effectiveness, *Elec. Light & Power*, vol. 18, pp. 40–43, October, 1940.

GILPIN, F. P., and S. H. POLLOCK: Double Saving by Switching Capacitors, *Elec. Light & Power*, vol. 20, pp. 38–41, September, 1942.

HOEHN, E. H.: Application of Automatic Shunt Capacitors, *Elec. World*, vol. 108, pp. 682–683, 736–737, August 28, 1937.

SANFORD, R. V.: Capacitors Switched by Automatic Unit, *Elec. West*, vol. 83, pp. 40–41, October, 1939.

SCHROEDER, T. W., E. W. BOEHNE, and J. W. BUTLER: Tests and Analysis of Circuit Breaker Performance When Switching Large Capacitor Banks, *A.I.E.E. Trans.*, vol. 62, pp. 821, 831, 1943.

STIVENDER, E. H.: Possibilities of Automatic Power Factor Regulation in Distribution Feeders, *Allis-Chalmers Elec. Rev.*, vol. 2, pp. 17–24, September, 1937.

CHAPTER 8

SERIES CAPACITORS FOR LINE-REACTANCE COMPENSATION

TRANSMISSION-LINE SERIES CAPACITORS

As transmission distances increase the line reactance becomes a problem of greater importance. To continue increasing the transmitted voltage rapidly increases line costs. For very long distances, power limit or stability considerations and load and line kvar requirements tend toward a rapid rise in unit power costs.

The possibility of using series capacitors to compensate for line reactance of long transmission lines has been studied for many years. Obviously, the series-capacitor voltage rating must be chosen on the basis of the maximum expected continuous load on the line, rather than the voltage which may appear on the series capacitor during heavy line faults. This is because of the fact that the cost of a given capacitive reactance increases as the square of its voltage rating. The only practical solution, therefore, lies in choosing the capacitor with a voltage rating corresponding to its normal working voltage, and by means of a by-pass device, limiting the voltage on the series capacitor to a value that will not damage the insulation in the capacitor during line fault.

When, however, a series capacitor is installed for the purpose of increasing line-to-load capacity, there is a very definite limit to the time that may elapse following a period of line fault before the by-pass is removed and the series capacitor is restored to the circuit. The by-pass device, therefore, must be effective at once when a fault occurs, thus limiting the initial voltage on the series capacity, and it must be effective for the duration of the line fault. It must then cease to be effective within a few cycles after the line fault has been cleared.

The application of transmission-line series capacitors was analyzed rather completely by Starr and Evans in a paper presented at the Summer Convention of the A.I.E.E. in Chicago, June 22–26, 1942. The title of this paper is "Series Capacitors for Transmission Circuits." Other papers and articles dealing with the approach to the problem of improved transmission of electrical power are listed in the bibliography.

SERIES CAPACITORS ON DISTRIBUTION CIRCUITS

The use of series capacitors to cancel or compensate for the reactance of distribution circuits so as to minimize voltage dips does not involve the requirement that the capacitor be quickly restored after a fault. This, and because these applications are small and easily tried out, has resulted in numerous such installations during the last few years.

Application of series capacitors to distribution circuits, while theoretically as simple as the use of shunt capacitors, involves several factors that must be considered carefully if the installation is to operate properly. The choice of capacitor is dependent both on the maximum and the momentary current it must carry and provision must be made to by-pass currents in excess of normal values. A careful analysis of the conditions under which the series capacitor is to operate must be made. If these conditions change, in all probability the capacitor must be altered to fit the new circumstances.

Field of Application on Distribution Circuits. A capacitor connected in series with an electrical circuit effectively cancels inductive reactance in the circuit and thus improves voltage regulation. It is particularly useful on circuits where lamp flicker is encountered because of rapid and repetitive load fluctuations such as are caused by spot-welding machines or motors driving reciprocating loads. In such cases voltage regulators are not sufficiently rapid to follow these sudden fluctuations. The voltage dip cannot be prevented by regulators since the dip itself is used to initiate the correction. A series capacitor serves as an automatic voltage regulator with practically instantaneous response and may be effective in reducing flicker caused by any type of fluctuating load.

Even when lamp flicker is not present, a series capacitor can be used instead of a transformer-type regulator to improve voltage regulation on a circuit having a high reactive voltage drop. In general, the regulator is less expensive; however, the capacitor may be justified on long circuits, of 2,400 volts or above, that supply small amounts of power.

A series capacitor improves voltage regulation by compensating for the voltage drop caused by reactance in the circuit; therefore, the improvement that can be obtained depends upon what portion of the voltage drop is caused by circuit reactance. It will give a worth-while improvement in voltage when the following conditions exist:

1. The circuit reactance is equal or greater than the circuit resistance.
2. The load has a low power factor.

Series capacitors should be considered only when a power-factor correction of the load with shunt capacitors does not give the desired results. When a low-power-factor load causes an excessive steady-state voltage drop, the condition should be corrected with a shunt capacitor rather than a series capacitor.

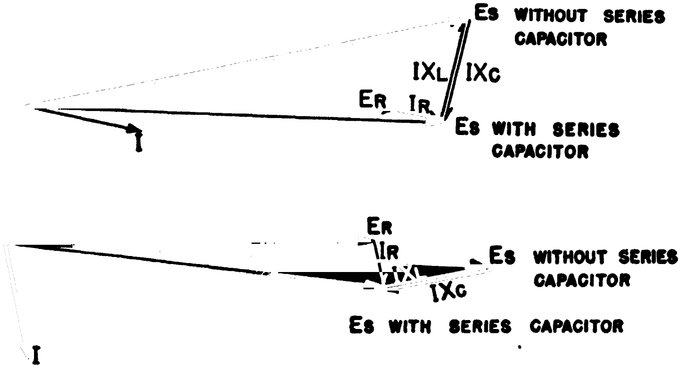


FIG. 106. Effects of adding series capacitance to lines of identical resistance vary considerably with the power factor of the load. There is relatively little difference between the magnitudes of the receiver voltages E_s with and without series capacitance in the upper illustration for a high-power-factor load. In the lower vector diagram, where a low-power-factor load is shown, compensating for the inductive-reactance drop with series capacitance drop makes a large difference.

Principle of Operation. The voltage drop on one phase of an electrical circuit having a lagging power factor can be computed approximately as follows:

$$\text{Voltage drop with or without series capacitor} \\ = IR \cos \theta + I\,(X_L - X_C) \sin \theta \qquad (1)$$

where R = total circuit resistance.
X_L = total circuit reactance.
X_C = series capacitance, if used.
I = load current.
θ = power-factor angle of the load.

From this expression it is seen that with high-power-factor loads ($\cos \theta$ large, $\sin \theta$ small), the resistance drop in the circuit is a large portion of the total drop and the reactance-drop portion of the equation is of little consequence. In such cases, a series capacitor is usually not effective. If the power factor of the load is low ($\cos \theta$ small, $\sin \theta$ large), the voltage drop caused by the reactance will become appreciable, particularly if X_L is large, and a series capacitor can be used to advantage since it has the effect of directly compensating for the inductive reactance X_L. The vector diagram of Fig. 106 shows the effects of adding series capacitance with both conditions of load.

If the reactance of the capacitor is made equal to the reactance of the circuit, there will be no steady-state reactive drop and the circuit will behave essentially as if there were only resistance present.

If the load power factor is low and nearly constant for all values of load current, the reactance of the capacitor can be made greater than the inductive reactance of the circuit in order to compensate in part or in whole for the resistance drop in the circuit. If the load power factor varies as it usually does on distribution circuits, the regulation can be improved in some cases by overcompensation. Such an application should be made only after a careful study of load distribution and variation.

Location of the Series Capacitor. A capacitor connected in series with a distribution circuit causes an increase in the line voltage on the load side of the capacitor. The magnitude of this increase is approximately equal to $I X_C \sin \theta$. On a circuit having a single load at the end of the line, the voltage at the load will be the same for any location of the capacitor. When loads are distributed along the line, however, it is desirable to locate the capacitor so that the voltage distribution along the line is most nearly uniform. In general this is accomplished when the capacitor is placed so that the voltage drop between the source and the capacitor is equal to one-half the rise produced.

It should be recognized that transformer excitation becomes decidedly nonlinear when the impressed voltage exceeds the normal voltage rating of the transformer. The series capacitor must not be located just ahead of a transformer bank or where it will boost the voltage impressed on the transformer primary to a point where excessive saturation will occur in the transformer. If such a condition does exist, suddenly applied loads may cause ferroresonance effects in the transformer due to the presence of the series capacitor.

Series-capacitor Protective Equipment. *Protection During Line Fault.* The condition which must be given first consideration is the voltage which may appear on the series capacitor as a result of a fault on the line beyond the series capacitor. This type of protection is usually termed "protection during line fault."

In most circuits in which series capacitors are applied, the currents and corresponding capacitor voltages during fault conditions are many times the maximum working value. Since it is customary to limit momentary voltage on capacitors to 200 per cent of their rated working voltage, it is necessary to use capacitors with continuous current ratings equal to 50 per cent of the maximum current that may flow during a fault or to use a voltage-limiting device. For a given reactance the cost of capacitors increases approximately as the square of the rated current, so that it is usually much more economical to use capacitors whose ratings are based on the working current and to limit the voltage that can appear across their terminals by means of auxiliary apparatus.

Care must be used that the voltage rating of the series capacitor and its associated protective equipment is made high enough so the capacitor is not by-passed during working loads. To insure availability of the series capacitor duirng motor-starting currents—when its effects are most useful—capacitor rating must be at least 67 per cent of the greatest motor inrush current that may be imposed on the line. With protective devices set to by-pass the capacitor at a safe value of 200 per cent of this rating, the capacitor will remain in service during such transient loads.

An illustration of such an application is the case in which a 5-ohm series capacitor is to be installed in a circuit on which several large motors are connected. The largest motor draws an initial starting current of 200 amp. This produces a momentary voltage of 1,000 volts on the series capacitor. The continuous-voltage insulation class of the capacitor should be 67 per cent of this, or 665 volts, while the protective gap should be set at 1,330 volts. The continuous-current rating of this series capacitor should be 665/5, or 133 amp. Quite often, as in this case, the continuous-current rating of the series capacitor is determined by the momentary current rather than the actual continuous current load in the circuit.

The device used to protect a series capacitor during a fault must not allow the voltage to rise substantially above twice the rated value even for a short time. The capacitor must be by-passed during the first half cycle of fault current. A properly designed gap fulfills this requirement and materials can be selected to give a stable arc and a low arc drop without repetitive restriking. Under most conditions some means must be provided for shunting this gap and transferring the arc current to another path. After the circuit current again falls to normal, the by-pass equipment must open to transfer current back to the capacitor. This is commonly done with a thermal or magnetic contactor, or by an automatic circuit breaker that closes to by-pass the gap and capacitor and opens some time after the fault has cleared to restore the capacitor to service.

Where the insulation class of the series capacitor is low—for example, where 230-volt capacitor units are used and the gap must break down at 460 volts—it is not possible to set the gap for sufficiently low breakdown voltage. In such cases a trigger circuit is used to initiate the breakdown of the gap. This is a circuit arrangement which initiates power current flow across the gap corresponding to a predetermined value of voltage on the capacitor. The gap current is initiated by superimposing a high-frequency high voltage on the gap.

Overload Protection. The device described above for protecting the capacitor during a line fault does not prevent operating the capacitor slightly above the rated continuous voltage, yet such overvoltage may damage the capacitor due to excess operating kvar.

Standard capacitors should not be used for continuous operation at an average more than 105 per cent of their rated voltage. Consequently average working current through a series capacitor should not exceed the rated working current by more than 5 per cent. The short-circuit protective device is not designed to function at less than 200 per cent of the rated current; therefore, it is sometimes desirable to provide overload as well as short-circuit protection. The overload protective device should have an inverse time-current characteristic that can be coordinated with the capacitor to allow momentary overloads but not continuous ones.

This special type of protection is usually not warranted except on large series-capacitor banks. The absence of overload protection on small distribution installations further emphasizes the need for care in choosing the continuous current rating.

Dielectric-failure Protection. Dielectric-failure protection is rarely used except on large banks. This also is a feature that is sacrificed on small distribution series capacitors in the interest of simplicity and low first cost.

Dielectric protection is a means of detecting a faulted capacitor unit in a series-capacitor assembly. In an unfused capacitor bank a short-circuited capacitor may sustain an internal arc which will cause gas to be generated in the unit. Continued operation will cause the internal pressure to reach a value which will rupture the case and possibly cause damage to other units and equipment. If the units are equipped with individual fuses, a fuse operation to remove a faulted unit increases the reactance of the bank and operation at the rated current of the original bank will subject the remaining units to overvoltage. A protective device for dielectric failure protection is spring biased to the closed position and latched open. A small solenoid mechanism is used to trip the latch when the currents become unequal in two equal branches of the capacitor. The switch stays closed and the capacitor is by-passed until the defective unit is replaced and the switch reset manually.

Series-capacitor Installations. Series capacitors operate at line potential; therefore, they must be insulated from ground for the line-to-ground voltage. This may be accomplished in a variety of ways.

For circuits 7,200 *volts or lower* the capacitor unit cases can be insulated for the line-to-ground voltage of the circuit and the capacitor cases operated at ground potential. These units can be supported on poles in conventional hanger-type brackets. In such an installation the protective device panel should be housed in an outdoor weatherproof enclosure with insulation for the line-to-ground voltage. The protective device can then be mounted on the pole with the units it protects. The most convenient arrangement usually results when the capacitor assembly for each phase is mounted on a separate pole.

For circuits above 7,200 *volts* it is not economical to build the line-to-ground insulation into the capacitor cases. It is therefore necessary to support the units in a structure that is insulated from ground and operates at line potential. This usually takes the form of an insulated platform supported on poles or a set of insulated rails in a substation structure. In such an installation, the protective device is enclosed in a housing insulated for the voltage across the capacitor terminals. This housing has only one bushing, the housing itself serving as the other terminal. The protective device is mounted on the same insulated platform that supports the capacitors and operates at the line potential.

Indoor-type capacitor units can be assembled in either indoor or outdoor housings. Here the protective device is built into the housing.

On circuits 13.8 *kv and below* the equipment for all three phases can be enclosed in one housing with six roof bushings. The capacitor units are mounted on insulated rails inside the housing. Usually the protective panels are mounted on the insulated rails with the capacitors.

On circuits above 13.8 *kv* the equipment for each phase is usually enclosed in a separate housing. The housing insulation and roof bushings are designed for the voltage across the capacitor and the entire housing is supported on insulators designed for the line-to-ground voltage of the system.

Switching Accessories. A series capacitor acts as a voltage regulator that is entirely automatic in its operation; therefore, there is no occasion to remove it from service except for inspection and maintenance. If it is possible to deenergize the line for this purpose, no switching equipment need be associated with the capacitor.

If it is desirable to remove a series capacitor without interrupting service over the circuit, it can be by-passed with a disconnecting switch as shown in Fig. 107. Such a switch must discharge the capacitor and carry the line current when closed and must transfer current back to the capacitor when opened. To prevent burning of the switch contacts, the switch must be equipped with the arcing horns. The switch chosen should have a voltage rating of the line voltage of the circuit and a current rating equal to or greater than the full-load current of the circuit.

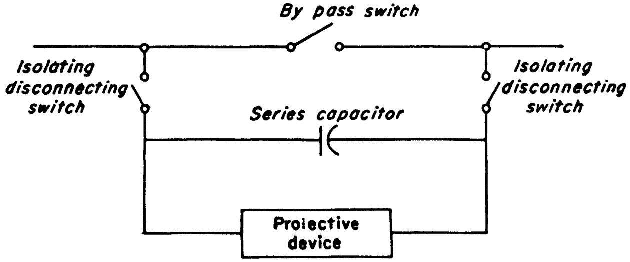

By pass switch
Isolating disconnecting switch
Series capacitor
Isolating disconnecting switch
Protective device

FIG. 107. A series capacitor, since it is connected directly into a line, must have protective equipment to shunt the capacitor when fault currents exceed its rating and the series-voltage drop increases to undesirable values. Shunting switches are also desirable at times to by-pass the device when it must be removed for service.

In addition to the by-pass switch, two disconnecting switches are required to isolate the capacitor from the line as shown in Fig. 107. These switches should have the same rating as the by-pass switch.

Application of Series Capacitor. The resistance and inductive reactance of the distribution circuit must be known before the improvement in voltage realized for different sizes of series capacitors can be calculated. Both of these quantities can be obtained from any engineering handbook. Impedance of transformers is usually given on the name plate or can be obtained from the manufacturer.

The problem of computing the circuit resistance and reactance may be complicated somewhat if there are one or more transformers in the circuit between the substation bus and the capacitor. In such a case all constants of lines and transformers must be reduced to their equivalents at the voltage of the section on which the series capacitor is to operate. Thus if a series capacitor is to be installed on a 2,400-volt circuit supplied through a transformer from a 13,800-volt line, the resistance and reactance of the 13,800-volt line and the transformer must be reduced to equivalent value of a 2,400-volt circuit. In this case, the ratio between the 2,400 volts of the capacitor section and the 13,800 volts of the circuit being computed is as one to six, and both the resistance and reactance of the 13,800-volt line must be multiplied by one-sixth squared, or one thirty-sixth. If the transformer impedance was measured on the high-voltage side in this case, it too must be multiplied by this ratio.

When the circuit constants and load are known, the improvement in voltage that can be realized for different values of X_C can be calculated using Eq. (1). The value of X_C that is chosen should be the smallest value that will give satisfactory regulation. It should not be made greater than X_L except under special conditions, as where overcompensation has definitely been proved to be desirable.

Series-capacitor units are designed to withstand a momentary voltage equal to 150 per cent of the rated voltage. For this reason the momentary load current should not exceed 150 per cent of the rated current. When there is a fault on the line the current may rise to a value many times the full-load current so that protective devices are used to by-pass the capacitor during these periods. The protective devices protect the capacitors by means of gaps which are set to break down between 150 and 200 per cent of the rated capacitor voltage. It is not desirable for the protective devices to operate on momentary load current peaks such as might be caused by motor starting or the operation of one or more resistance welding machines. *The rms value of the greatest momentary load current should never exceed* 150 *per cent of the current rating of the capacitor.*

The current rating of a series capacitor should be chosen so that the following limits are never exceeded:

1. The sustained current should not exceed 110 per cent of the capacitor rating and the average current over any 24-hr period should not exceed 105 per cent of the capacitor rating.
2. The rms value of the greatest momentary load current should not exceed 150 per cent of the capacitor continuous rating.
3. Series-capacitor banks are usually made up by combining capacitor units to obtain the desired reactance and continuous voltage rating. The series-capacitor units that are in common use today are shown in Table 20.

The above capacitors can be combined to obtain the desired series-capacitor reactance and voltage rating as follows:

1. Determine desired series-capacitor reactance and continuous current rating.

2. Multiply the rated series-capacitor current by the desired reactance to obtain the rated working voltage.

TABLE 20. RATINGS OF SERIES-CAPACITOR UNITS

Rated voltage	Rated kva	Reactance, ohms	Rated current, amp
230	7.5	7.05	32.6
330	13	8.38	39.4
400	15	10.7	37.5
425	15	12.0	35.3
460	15	14.1	32.6
485	15	15.7	30.9
515	15	17.7	29.1
575	15	22.02	26.1
660	15	29.0	22.7
705	15	33.0	21.3
750	15	37.5	20.0
815	15	44.5	18.4
895	15	53.5	16.8
1,000	15	66.5	15.0
1,200	15	96.0	12.5
1,320	15	116.0	11.4
1,470	15	144.0	10.2
1,600	15	171.0	9.37
1,740	15	204.0	8.62
1,920	15	246.0	7.81
2,200	15	323.0	6.82
2,400	15	384.0	6.25
2,640	15	465.0	5.68
2,900	15	561.0	5.17
3,180	15	674.0	4.72
3,480	15	808.0	4.31
3,750	15	938.0	4.00
4,160	15	1,160.0	3.60
4,800	15	1,540.0	3.12
7,200	15	3,460.0	2.08
7,960	15	4,230.0	1.88

3. Select a capacitor unit from the table having an equal or next higher voltage rating.
4. From the table read the reactance of the unit selected and divide this by the desired series-capacitor reactance. This gives the

number of units required. If it does not come out a whole number, use the next larger whole number of units.

Example.

Given: A 4,800-volt distribution circuit with a full-load current of 100 amp and a maximum momentary current of 170 amp at 60 per cent power factor. The circuit is fed from a 13.2-kv bus through three 500-kva 2.6 per cent reactance transformers. It consists of a three-wire line 5 miles long. The conductors are 4/0 cables and are spaced 21¾ in. between centers on horizontal crossarms.

Find: Series capacitor that will reduce the voltage regulation peaks to 8 per cent.

Transformer reactance per phase =

$$\frac{4{,}800^2}{(500 \times 1{,}000)} \times 0.026 = 1.20 \text{ ohms.}$$

Spacing phase 1 to phase 2 = 21¾ in.
Spacing phase 2 to phase 3 = 21¾ in.
Spacing phase 1 to phase 3 = 43½ in.
Effective spacing = $\sqrt[3]{21\frac{3}{4} \times 21\frac{3}{4} \times 43\frac{1}{2}} = 27.4$ in.

The reactance is found from tables in an engineering handbook to be 0.595 ohm per mile.

Line reactance = $5 \times 0.59 = 2.95$ ohms.
Total circuit reactance = $1.20 + 2.95 = 4.15$ ohms.
Resistance of conductors = 0.30 ohm per mile.
Resistance of transformer = 0.5 ohm per phase.
Total circuit reactance = $(5 \times 0.30) + 0.50 = 2.00$ ohms.
Using Eq. (1),
The maximum voltage drop without the series capacitor =

$$(170 \times 2.00 \times 0.6) + (170 \times 4.15 \times 0.8) = 204 + 565 = 769 \text{ volts.}$$

The regulation without the series capacitor =

$$100 \times \frac{769}{4{,}800/1.732} = 27.7 \text{ per cent.}$$

It is desired to reduce the maximum regulation of the circuit to 8 per cent.

$$\text{Voltage drop at 8 per cent regulation} = \frac{4{,}800}{1.732} \times 0.08 = 222 \text{ volts}$$

Using Eq. (1),

$$222 = (170 \times 2.00 \times 0.6) + 170\,(4.15 - X_C)\,(0.8)$$

from which

$$X_C = 4.02 \text{ ohms}$$

Assume that during the simultaneous operation of two spot welders on this circuit the momentary current rises to 170 amp and all other times it is less than 100 amp. The capacitor must have a continuous current rating of 170 divided by 1.5, or 113 amp, if its momentary current rating is to be limited to 150 per cent.

The rating of the series capacitor required for each phase is now determined to be 4.02 ohms, 113 amp. With this information a standard series capacitor unit can be chosen from the table.

$$\text{Capacitor rated working voltage} = 113 \times 4.02 = 454 \text{ volts}$$

From the table the next higher voltage rating is selected, which is 460 volts. From the table it is seen that each 460-volt unit has a reactance of 14.1 ohms.

$$14.1/4.02 = 3.52$$

The nearest even number of units above 3.5 is 4, so the preferred rating of the series capacitor for this application will be four 460-volt units per phase and the nearest rating of the series capacitor will be 3.52 ohms at 130.4 amp continuous current and 195.6 amp momentary load.

Special Application Problems. One of the most frequent causes of trouble has been the failure to select the basic rating of the series capacitor sufficiently high with respect to instantaneous load currents so as to avoid the operation of protective devices by these momentary loads.

Care must be used to avoid boosting transformer voltages into the nonlinear range where resonance effect may be troublesome.

The effect of a series capacitor on the operation of an electrical system cannot be predicted without a detailed study taking into account all the possible loads on the system in all their combinations. Certain loads, particularly those that draw currents containing large harmonic or subharmonic components, may be resonant with the capacitive reactance under certain conditions and improper operation will result. If such difficulties are encountered they can be corrected by changing the size of the capacitor or, in other cases, by shunting the series capacitor with a resistance.

The principal problem in the operation of circuits with series capacitors arises in *starting large induction or synchronous* motors. Such a system may be resonant at some speed less than synchronous. This is particularly true if the motor-starting load predominates. Under these conditions the motor will come up to partial speed and continue to rotate at this reduced speed. Trouble of this nature can be eliminated by shunting the series capacitor with a resistance. This is a particularly good method since at system frequency little of the current is by-passed but at the lower frequency of resonance sufficient current is by-passed to prevent resonant effects. A series capacitor installed on a system that has a motor larger than 10 per cent of the full-load circuit kva should have a shunt resistor. If this resistance is not more than ten times the capacitive reactance, the chances of difficulty are remote.

If the transformer primary voltage is boosted substantially, as for example, when energizing the line, or when the load suddenly increases, some saturation may take place resulting in ferroresonance. These conditions, like those for motor starting, can be corrected by shunting the series capacitor with a resistance of the order of ten times the capacitor ohms. Transformer saturation may also occur if the load current drops sharply, permitting the series capacitor to produce a large d-c component in the transformer primary. This is also subject to correction by a resistor permanently connected in parallel with the series capacitor.

It must be recognized that the results to be expected with a series capacitor are not as predictable as with a shunt capacitor nor can series capacitors be applied with the same ease as shunt capacitors, or with the same guarantee of results. Shunt capacitors simply draw a leading current of known magnitude and are unaffected by other equipment on the system. Series capacitors, however, modify the characteristics of the entire circuit and can only be dealt with successfully in terms of system performance.

In making an economic analysis comparing the cost of series capacitors with other solutions, such as new lines; raising voltage levels; etc., the entire cost of the series capacitors should include the necessary careful study of the application and cost of the protective equipment.

The use of series capacitors has made possible the solution of many difficult problems associated with voltage dips that could not have been resolved in any other way.

TYPICAL INSTALLATION OF A SERIES CAPACITOR ON A POWER CIRCUIT

A manufacturing plant using heavy welding operations found that the voltage fluctuated 15 to 20 per cent at the plant bus due to the heavy welder load. These voltage dips not only caused lamp flicker but frequently bad welds. It was impossible to adjust the various automatic welders to operate properly with this fluctuating voltage and considerable loss of production resulted. Figure 108 shows the supply from the power substation to the plant over a 4,600-volt line being stepped down to 220 volts at the plant bus. The series capacitors were

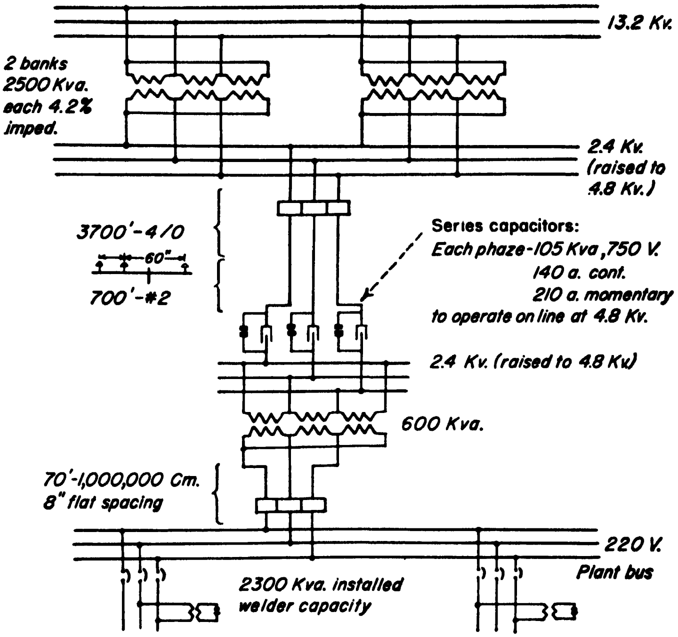


FIG. 108. Power supply to industrial plant showing location of series capacitors.

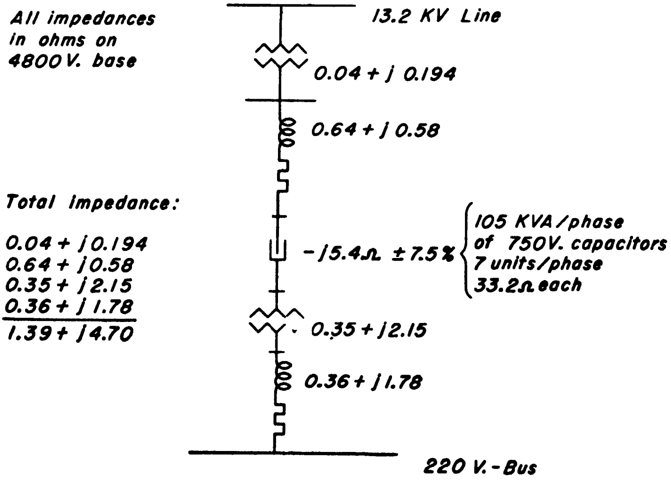


FIG. 109. Impedance diagram showing series capacitors.

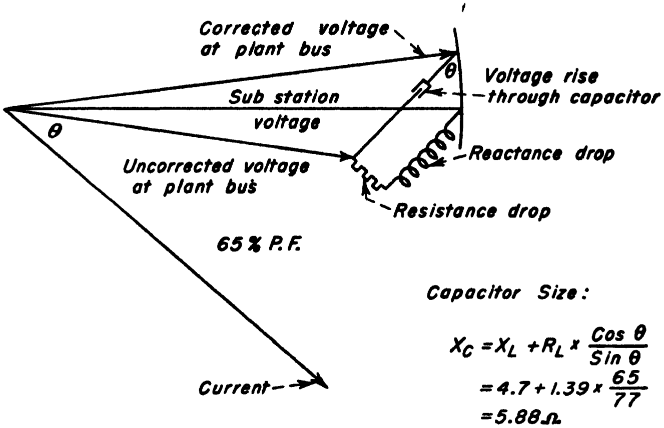

Corrected voltage at plant bus
θ
Voltage rise through capacitor
Sub station voltage
θ
Reactance drop
Uncorrected voltage at plant bus
Resistance drop
65 % P.F.
Capacitor Size:
$X_C = X_L + R_L \times \frac{\cos\theta}{\sin\theta}$
$= 4.7 + 1.39 \times \frac{65}{77}$
$= 5.88\Omega$
Current

FIG. 110. Vector diagram showing series capacitors.

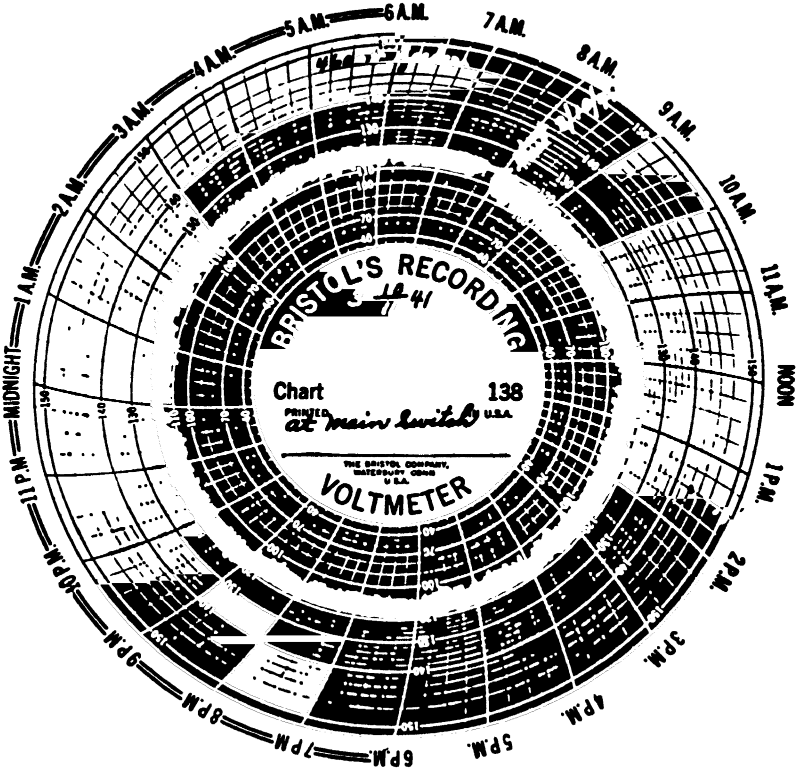


FIG. 111. Voltage record before installation of series capacitor.

connected on the 4,600-volt side of the transformers. The circuits to the various welders within the plant are also shown. Figure 109 shows the impedance diagram, the impedance from the power-company 13.2-kv bus to the plant bus being 1.39 ohms resistance and 4.7 ohms reactance.

The vector diagram covering this case is given in Fig. 110. It is found that 1.18 ohms of overcompensation would be required to fully take care of resistance. Added to 4.7 ohms to neutralize reactance, this makes 5.88 ohms. A series capacitor having a reactance of 5.4 ohms was used since this was the nearest rating that could be conveniently obtained with standard capacitor units. This gave only 0.7 ohm overcompensation. The voltage fluctuation before the installation is shown in Fig. 111 and after by Fig. 112. The results were very satisfactory.

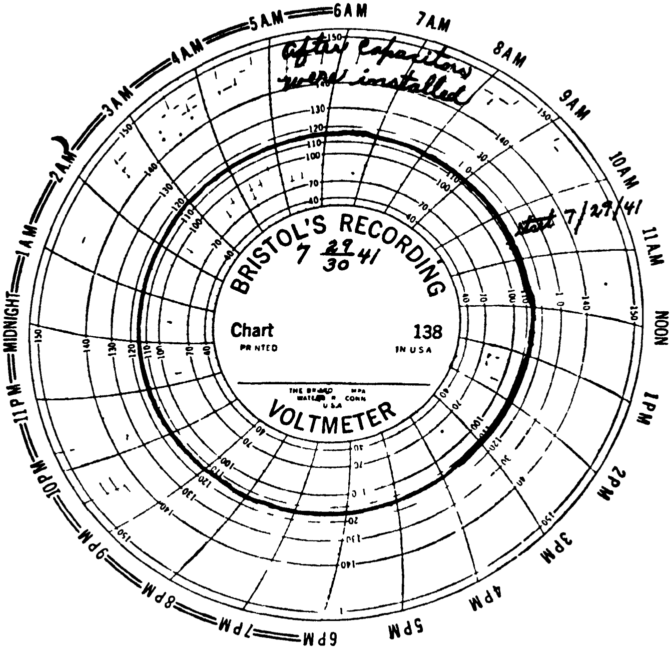


FIG. 112. Voltage record after installation of series capacitor.

Figure 113 shows the installation of the capacitors and their protective devices.

TYPICAL INSTALLATION ON A HIGH-VOLTAGE TRANSMISSION LINE

The presence of considerable reactance in a line becomes quite objectionable when the line serves a large industrial load made up of arc furnaces, especially when power is taken from the same circuit for lighting and other loads.

Such a condition was encountered by a large utility that serves a steel-mill load over a 14-mile open-wire 66-kv line. The steel mill received its power from this line through four step-down transformer banks operating in parallel. The banks had a name-plate rating of 44,200 kva and were connected 66,000/12,000 volts; the windings were delta-connected on the high side and Y-connected on the low side, with the low-side neutral solidly grounded.

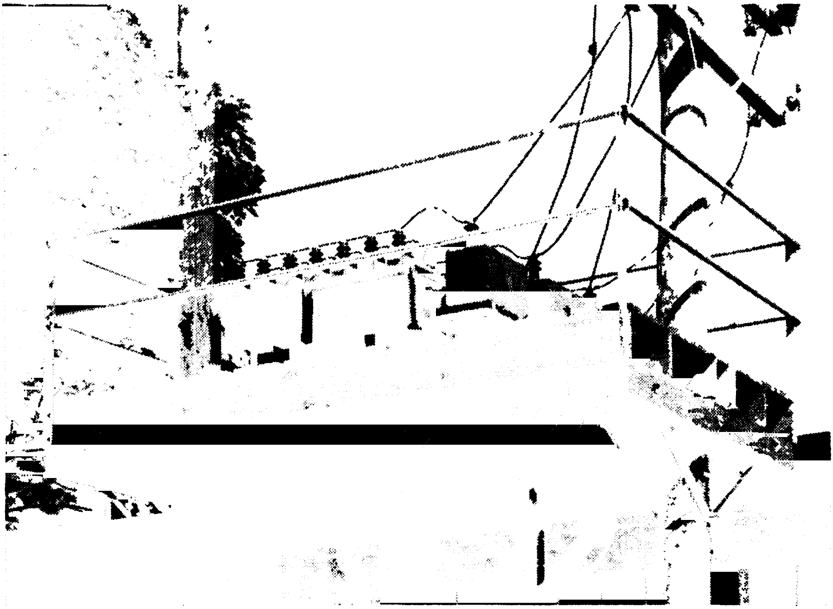


FIG. 113. Series capacitor installation to reduce dips in voltage caused by welder loads.

The load at the steel mill consisted mainly of four 10,000-kva electric-arc furnaces, one 4,000-hp induction motor-generator set, one 800-hp synchronous motor, two 3,000-hp synchronous motors, and two 1,000-kva synchronous motor-generator sets. Additional load was expected in the future.

The electric-arc furnaces caused rapidly fluctuating loads to be drawn from the 66-kv line. The voltage variation during the operation of melting down in the furnaces was considerable. In addition, the rapid fluctuations in the furnace load caused severe instantaneous voltage dips.

These wide fluctuations were not too serious as far as furnace operation is·concerned; however, the sustained periods of low voltage and unbalance in voltage due to furnace operation caused frequent trouble in motor operation, both starting and running, generally making it difficult to start certain motors except when the plant load was light.

A nearby town had been supplied with power over a 22-kv line tied into the 66-kv circuit, but due to the unsatisfactory voltage as a result of these load fluctuations, it was necessary to discontinue service over this tap and supply this lighting load over another relatively long and uneconomical 22-kva line.

Various methods for correcting this condition were considered as follows:

1. Voltage regulator for the motor load.
2. Synchronous condenser.
3. Switched shunt capacitors.
4. Another 66-kv line.
5. Compensation of the 66-kv line reactance with a series capacitor.

Voltage Regulator. The voltage regulator might have solved the problem of starting the motors and corrected for the prolonged periods of low voltage, but reconnecting the motor load to a regulator would have been expensive; and since the regulator would not be capable of correcting the flicker or sudden changes in voltage, it would only have solved the problem to a small degree.

Synchronous Condenser. While a synchronous condenser connected at the load would have been effective in reducing lamp flicker as well as correcting for steady-state changes in voltage, a synchronous condenser to accomplish this at the steel-mill bus would have been found to be quite large and expensive, the losses quite considerable, and the annual cost of operation substantial. In addition, valuable space would have been required to locate the synchronous condenser.

Shunt Capacitors. Consideration was given to connecting a group of shunt capacitors to each of the four furnace circuits, to be switched with the furnace and to connect another unswitched group of shunt capacitors to the 11-kv bus at the steel mill.

While shunt capacitors would supply reactive kvar to the load, the amount of kvar required by this type of load varies over such a range that it is impractical simply to switch the capacitors with the furnaces. To switch the capacitors as needed would present even a greater problem due to the tremendous number of switching operations that would be required. Even assuming the shunt capacitors could be applied in a manner to improve the steady-state power factor of the load, they would not prevent the sudden voltage changes that cause the lamp flicker, and, in fact, would very likely aggravate the condition.

Second 66-kv Line. A second 66-kv line from the power source to the steel mill was considered as a method of reducing the voltage flicker and improving the voltage regulation. With two lines to the steel mill, the minimum voltage on the 11-kv bus would be raised from about 98 to 104 volts, and such a line would have been expensive for such a small improvement.

Series Capacitor. A series capacitor was found to be the best solution, as it was fundamentally suited to reducing flicker and improving voltage, doing both efficiently and at a low cost. It is inherently automatic in operation because it introduces a voltage which leads the current 90 deg and is directly proportional to the magnitude of the current. The capacitive reactance voltage instantaneously compensates for a like amount of line inductive reactance voltage for all values of current, reducing both instantaneous and prolonged changes in voltage caused by circuit reactance.

Since a series capacitor reduces the impedance of the line, it, in effect, increases the capacity of the line because of increased utilization voltage. In other words, increased kva loads can be carried with the same voltage drop or the same kva can be carried with less current.

Rating and Location of the Series Capacitor. Series capacitors are rated in ohms and current. Both the continuous and momentary current must be considered. The momentary current is the highest current at which the benefits of the series capacitor must be available. It is assumed that the series capacitor can be by-passed where the actual current exceeds the momentary current rating.

Calculations indicated that the inductive reactance from the power source to the steel mill's 11-kv bus must be reduced approximately 14 ohms in order to raise the minimum voltage to 110 volts with the desired loads of 30,000 kva and 80 per cent power factor. A capacitive reactance of 14 ohms was sufficient to compensate for all of the line reactance of 11.49 ohms plus most of the system reactance at the source bus of 3.59 ohms.

Although the load on this line was less than 500 amp, it was considered desirable to install a series capacitor having a continuous current rating of 500 amp consisting of three groups of 2,400-volt 15-kvar capacitors in series per phase and each group consisting of 80 capacitors in parallel. This gave nominal capacitive reactance of 14.4 ohms and a series capacitor rating of 3,600 kvar per phase.

A series capacitor having a continuous-current rating of 500 amp has a momentary rating of 150 per cent, or 750 amp for durations of 5 min, in accordance with established rating practice. This was thought to be ample for the expected operating range of the line.

The most favorable location of the series capacitor from the standpoint of the current was found to be at some point along the 66-kv line because placing it in the 11-kv bus would require a series capacitor with a very much lower reactance and much higher continuous-current rating. This higher current rating would introduce problems in connection with the by-pass accessories. The location of the series capacitor in the 66-kv line was determined by fault current and availability of a site for erection of the capacitor as well as other secondary factors.

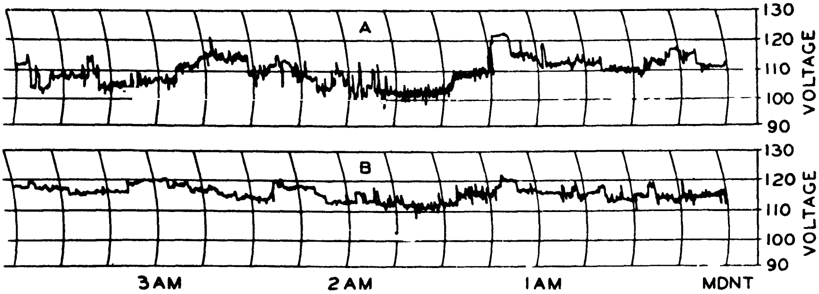


FIG. 114. Effect of series capacitor on voltage fluctuation near the major load point.

Effectiveness of the Series Capacitor. The effectiveness of the series capacitor in rasing the level of the voltage and reducing the spread is shown in the typical voltage charts, Fig. 114. These reflect the conditions on the 11-kv bus at the steel plant with and without the series capacitor.

The effectiveness of the series capacitor in reducing the lamp flicker on the circuit supplying the nearby town is shown in Fig. 115.

Description of the Series Capacitor. Placing a series capacitor in a 66-kv line presented several problems as follows:

1. Providing insulation to ground.
2. Providing means for by-passing the series capacitor during overload and fault-current conditions.
3. Providing means of automatically restoring the series capacitor to service following a fault and with the necessary time delay.

Each phase of the series capacitor consisted of a structural-steel housing containing 240 15-kva capacitor units forming a 7,200-volt single-phase 3,600-kva capacitor having one insulated terminal, with the housing forming the other terminal. This housing is 28 ft long, 3½ ft wide, and 9½ ft high and is supported on columns of 69-kv heavy-duty insulators.

A special-design gap is connected across each 80-unit group of capacitors inside of the housing and set to limit the voltage across the groups to double their continuous rated voltage. In parallel with each gap is a switch having a closing mechanism operated directly from gap current and designed in a manner to reopen after a time delay, thus restoring the series capacitor to service. The protective device requires no outside source of power for its operation and thus can be located within the housing above ground potential. The development of this type of protective device helped to make practical the use of a series capacitor in a high-voltage line, such as 66 kv, because had it been necessary to use a conventional by-pass breaker located at ground potential, the total cost of the installation would have been greatly increased.

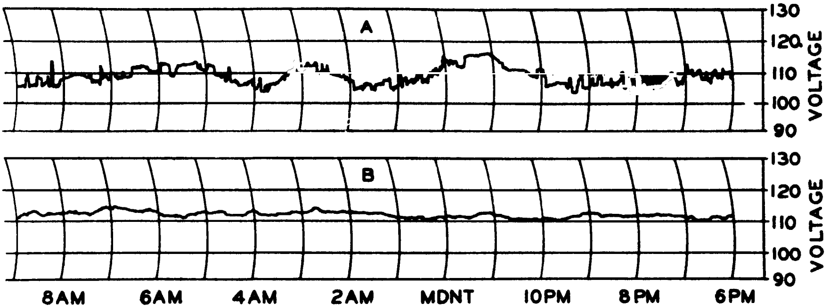


FIG. 115. Effect of series capacitor on voltage fluctuation in lighting circuit tapped off to serve a near-by town.

Figure 116 shows the 10,000-kvar capacitor housing on phase C, with the supporting columns of insulators, and the resistor which is in parallel. The resistor is in the aluminum-clad housing at the right, which is also supported on insulators for the line-to-ground voltage. The by-pass and isolating disconnects are also shown in part.

Effect of Series Capacitor on Motor Starting. The fact that the series capacitor maintained higher voltage was expected to greatly improve motor starting; however, the possibility of subsynchronous resonance under certain conditions of load and motor starting in connection with series capacitors is well known. It is, therefore, common practice to stabilize series capacitors by placing in parallel with them a resistor unit of suitable ohms. The effect of the parallel resistor is to either prevent or damp out subsynchronous resonance associated with motor starting and magnetizing current on power-transformer banks. It also damps resonance at any frequency.

Determination of Shunt-resistor Ohms. As stated above, a series capacitor is very effective in improving voltage conditions but motor starting may cause subsynchronous-resonance conditions. To prevent these undesirable operation conditions, a resistor of proper ohms in parallel with the series capacitor may be required. Such motor difficulties have been experienced on smaller series-capacitor installations and are known as "self-excitation" where the motor rotor locks in and rotates at some speed considerably lower than normal speed. When this happens, excessive subsynchronous current corresponds to the resonant frequency of the entire system when viewed from the rotor of the motor involved. Many factors determine whether or not a given motor will lock in at some subsynchronous speed when it is started:

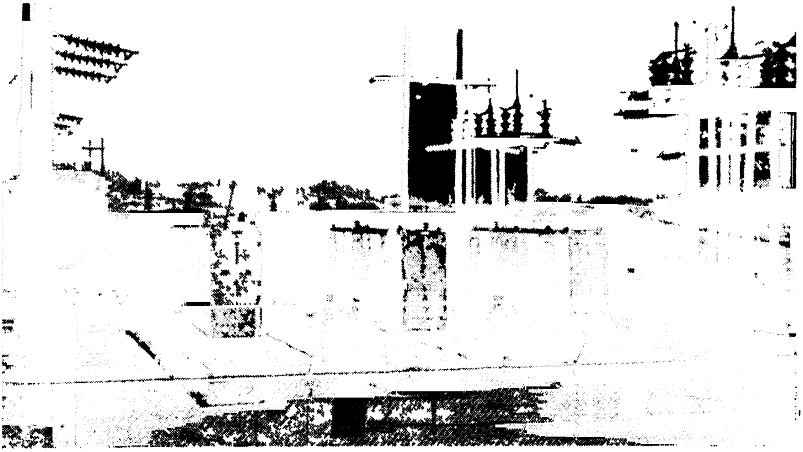


FIG. 116. View of a 10,000-kvar series capacitor being installed in a 66-kv transmission line. Rated working current is 500 amp Housings containing shunt resistors are shown in the foreground.

1. Speed of acceleration.
2. Other loads in parallel with the motor.
3. The power factor of the parallel load.
4. The type of starting device used.
5. The WR^2 of the motor and its load.

At the steel mill mentioned above there are in operation several large induction and synchronous motors. To determine beforehand whether any or all of these motors are susceptible to self-excitation after the installation of the 10,000-kva series capacitor, an extensive study of all known theories and formulas on the phenomenon of self-excitation was made.

The largest motor involved at the steel mill is a 4,000-hp wound-rotor induction motor having a very large flywheel. This motor drives two d-c generators. The motor when started accelerates at a very slow rate and, therefore, may not come up to proper operating speed due to the series capacitor.

It became apparent after some investigation that all of the larger motors and especially the 4,000-hp induction motor might self-excite after the installation of the series capacitor if no resistor was provided.

Each phase of the series capacitor was, therefore, provided with a parallel resistor which could be adjusted to several values from 100 to 400 ohms so that through experience the highest value could be determined for which resonance was nonexistent. Subsequent operation has shown that with 400 ohms no resonance is encountered on motor starting.

Bibliography

ALLEN, E. J., and J. L. CANTWEL: The Effect of Series Capacitors upon Steady State Stability of Power Systems, *Gen. Elec. Rev.*, pp. 279–282, May, 1930.

BUTLER, J. W., and C. CONCORDIA: Analysis of Series Capacitor Application Problems, *A.I.E.E. Trans.*, pp. 975–988, 1937.

CLARKE, EDITH, and S. B. CRARY: Stability Limitations of Long A–C Transmission Lines, *A.I.E.E. Trans.*, pp. 1051–1059, 1941.

JOHNSON, A. A., R. E. MARBURY, and J. M. ARTHUR: Design and protection of 10,000 KVA Series Capacitor for 66 Kv Transmission Line. A.I.E.E. General Meeting, Pittsburgh, Jan. 26–30, 1948.

JONES, B. M., J. M. ARTHUR, C. M. STEARNS, and A. A. JOHNSON: 10,000 Kva Series Capacitor Improves Voltage in 66 Kv Line Supplying Large Electric Furnace Load, A.I.E.E. General Meeting, Pittsburgh, Jan. 26–30, 1948.

MARBURY, R. E., and J. B. OWENS: New Series Capacitor Protective Devices, *A.I.E.E. Trans.*, vol. 65, p. 142, March, 1946.

MILLER, G. B.: Design and Layout of 66 kv, 10,000 kva Series Capacitor Substation, A.I.E.E. General Meeting, Pittsburgh, Jan. 26–30, 1948.

SHELTON, K. K.: The Series Capacitor Installation at Ballston, N. Y., *Gen. Elec. Rev.*, pp. 432–434, August, 1928.

STARR, E. C., and R. D. EVANS: Series Capacitors for Transmission Circuits, *A.I.E.E. Trans.*, pp. 963–973, 1942.

WAGNER, C. F.: Self-excitation of Induction Motors, *A.I.E.E. Trans.*, pp. 1241–1247, 1941.

CHAPTER 9

SERIES CAPACITORS DIRECTLY APPLIED TO SPECIFIC INDUSTRIAL LOADS

DISCUSSION OF RESISTANCE-WELDER LOADS

Certain types of loads in industrial plants require a considerable amount of reactance in proportion to the power consumed. Examples of these are melting furnaces and welders. Shunt capacitors may be effectively used to supply this reactance in the case of furnaces and other such devices which are on continuously, because one is usually interested merely in cutting down the steady-state current in the line and maintaining good power factor under steady-state conditions. Resistance welders, however, are usually characterized by a large intermittent kva demand at low power factor. In most welder applications the welder is energized for a very short period followed by a considerable period when no current is flowing. Generally the actual power consumed is relatively small and does not warrant heavy lines and large power-supply transformers capable of supplying the initial kva demand with reasonable voltage regulation.

In many locations the power company cannot serve large resistance welders because of the small revenue and high installed capacity required to serve them. If the power-source capacity is not adequate in relation to the high instantaneous kva demand, voltage dips will occur each time a weld is made. These dips in turn cause "flicker" problems. Flicker is particularly bad when lighting loads are supplied from the same lines, which is usually the case. Under these conditions the manufacturer must avoid the fabrication of large parts with this otherwise very attractive welding method, or he must perform these operations at some period prescribed by the power company when the voltage dips can be tolerated. Another alternative is for the manufacturer to install expensive rotating machines to balance these single-phase loads on a three-phase system and smooth out the intermittent load on the system by means of inertia.

Even when the voltage dips are confined to the internal circuits in the plant, these dips can become very serious where a number of welders are being used, because dips vary in magnitude according to the number of welds being made at a single instant; and when welders are adjusted to obtain satisfactory welds when operating alone, they may make bad welds when their operation is simultaneous with that of another welder.

A large part of the power company's difficulty in handling these momentary loads can be eliminated by cutting out the kvar portion of the demand with compensation for the reactance of the welder by a capacitor. This, however, cannot be done simply with a shunt capacitor permanently connected in parallel with the welder, because each time the welder and capacitor combination is energized a large inrush current will flow to charge the capacitor. After that the current in the line will drop down to a low value. If the period of the weld is very long, as, for example, 20 or 30 cycles, and one is primarily concerned with steady-state kva demand because of heating of supply transformer or conductors, the shunt capacitor so connected may meet the requirements. This usually is not the case because a great majority of welding operations are made up predominantly of starting transients with weld periods of 2 or 3 cycles, and the power company in many cases measures the instantaneous kva demand and uses it as a basis of a power contract.

The widespread acceptance of the resistance welder for high-speed fabrication of parts has imposed an enormous single-phase load on power circuits. The total load in resistance welders now installed in the United States totals more than 8 million kva.

USE OF SERIES CAPACITORS TO REDUCE INSTANTANEOUS DEMAND

In applying a series capacitor to a welder, the capacitor is chosen to compensate for the welder kvar. When this is done the inrush-current drawn by the welder is reduced to a value corresponding to the actual power peaks.

A series capacitor creates an out-of-phase voltage component that offsets the reactive voltage component in the welder; therefore the line peaks can be held at or near values that would be obtained if the inductance could be removed from the welder transformer and its throat. Many series capacitors have been used for this purpose and satisfactory results are obtained, especially in applications where the reactance of the welder does not vary widely, as is usually the case.

SHUNT CAPACITORS COMPARED WITH SERIES CAPACITORS

There are two essential differences between shunt and series capacitors. Shunt-capacitor units are designed with internal-discharge resistors to discharge them automatically after a time, when they are disconnected. Series capacitors, however, must hold their charge to avoid the recharging transient that would otherwise occur at the beginning of each weld. Hence, they are made without internal discharge resistors, and a separate means is used to discharge them only when the welding machine is to be shut down.

Shunt capacitors usually are rated to match up with standard line voltages. Series-capacitor voltage ratings are governed by the welder-machine design and characteristics, as well as by the line voltage. This necessitates a wide range of capacitor voltage ratings.

Also, shunt capacitors are rated on a continuous-voltage basis, usually operate continuously, and cannot be subjected to voltages much in excess of rating. They are applicable on circuits whose average voltage over a 24-hr period does not exceed the rated voltage by more than 5 per cent, or where the short-time operating voltage is not more than 110 per cent of the name-plate rating.

Series capacitors operate at a voltage that varies from zero to the voltage existing during weld, the period of which usually is small compared to the total time. The effective or equivalent continuous voltage, or heating kva, is therefore low and the capacitor operates at substantially room temperature. Therefore series capacitors usually are selected on the basis of voltage "during weld," and for a given design of capacitor this voltage is permitted to go to 50 per cent above that at which the same capacitor could operate continuously. For convenience, however, series capacitors usually are rated on the continuous basis.

A series capacitor installation consists of a number of capacitor units provided with a discharge device that normally is connected in shunt with the bank by a contactor when the welder is deenergized. Application of power to the welder energizes this contactor and keeps the discharge device disconnected while the capacitor is in use.

The welder and its series capacitor constitute a combination having an over-all voltage rating that is no longer the same as the line voltage to which the welder previously was applicable, because in reducing the kva demand the current has remained constant and the required voltage has been reduced. Therefore, when a welder is equipped with a series capacitor it is necessary to introduce a transformer to readapt it to the original line voltage.

In some instances a welder designed for use on 440 volts may be used on 220 volts after a series capacitor is added. Usually, however, the combination cannot be used without an additional transformer. An alternative is to rewind the welder so that the new combination is applicable to the circuit voltage. When a new welder is being supplied complete with a series capacitor there is, of course, no problem.

The design of the welder in all instances determines the voltage rating of the series capacitor. If the welder is designed for use on a 230-volt circuit it may be preferable to rewind it when adding series capacitors rather than add a transformer, because the former plan often results in the use of higher voltage capacitors that may cost less per kva. This factor should always be considered.

TYPES OF SERIES-CAPACITOR CONNECTIONS

If the welder is not to be rewound, two alternatives are possible. One is to place the transformer immediately ahead of the welder, as

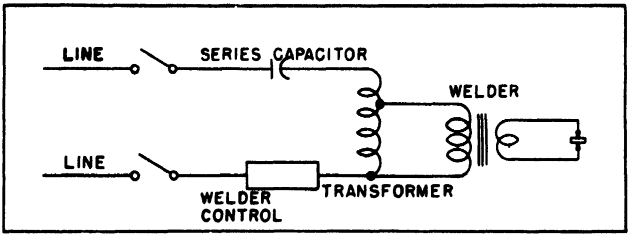


FIG. 117. An autotransformer used to permit operation of a welder with a series capacitor and avoid uneconomical capacitor ratings.

shown in Fig. 117. The other is to reduce the line voltage ahead of the series capacitor. In either event the tube control must be in series with the capacitor, so as to leave it charged when power is cut off by the control. If the series capacitor is placed between the transformer and the welder, and the tube control is in the line, the capacitor will be discharged after each weld. This cannot be tolerated.

This arrangement shown in Fig. 118 is not satisfactory if the voltage on the low side of the transformer is less than 230 volts because of possible failure of the tube to fire properly.

The arrangement shown in Fig. 117 is usually to be preferred because it enables one to select higher voltage capacitors and often obtain lower capacitor cost. The control tubes, however, are subjected to a higher voltage, which may in some instances favor the scheme shown in Fig. 118.

Obviously the application of series capacitors to resistance welders is not so simple as the application of shunt capacitors to ordinary low-power-factor loads. Since the fundamental design characteristics of the welder transformer must be known and the tube control also is affected, the makers of both the welder and the control must be consulted.

The characteristics of the welder transformer must be known in order to select the series-capacitor rating, and these data are not obtainable from the name plate. If data on the welder power factor "during-weld" are not available from the manufacturer, they must be obtained by tests.

The kva demand "during-weld" and the power factor are to be determined when using the largest throat opening provided, with a typical welding operation. These data are required to determine the capacitor reactance ohms needed. They are needed, also, under the condition when the welder electrodes are brought into direct contact to determine the need for protecting the capacitor against overvoltage at such times, or to form a basis for selecting the voltage rating of the capacitor.

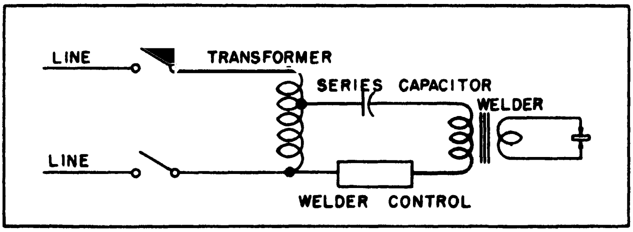


FIG. 118. Placing autotransformer ahead of welder and capacitor avoids high voltage on tube-control but is not satisfactory on voltages less than 230 volts.

DETERMINATION OF SERIES-CAPACITOR RATING

Tables 21, 22, and 23 provide a quick means of estimating the required size of a series capacitor. In these tables it has been assumed that the tube drop is 15 volts and the duty cycle will not exceed 44 per cent. Also that the "during-weld" period will never exceed 1 min. These assumptions apply in most cases.

Use of the tables can be more readily shown by the following example. Assume

During-weld kva = 350.
During-weld power factor = 42 per cent.
Kva with electrodes contacting = 450.
Power factor with electrodes contacting = 36 per cent.
Duty cycle = 44 per cent.
Line voltage = 230 volts.

TABLE 21. WELDER CAPACITOR-UNIT DATA, 230-VOLT 60-CYCLE LINE

Welder power factor	Capacitor ohms (per one welder kva) for unity power factor	Capacitor volts during weld	Welder primary volts during weld	Required capacitor		
				Capacitor continuous voltage rating	Maximum permissible short-circuit capacitor volts	Ohms per capacitor unit
(1)	(2)	(3)	(4)	(5)	(6)*	(7)
0.25	717.0	832	860	575	948	22.0
0.26	663.0	801	828			
0.27	612.0	767	797	515	850	17.7
0.28	566.0	738	768			
0.29	527.0	710	742	485	800	15.5
0.30	491.0	685	718	460	758	14.0
0.31	458.0	660	694			
0.32	428.0	636	672	425	700	12.0
0.33	401.0	615	652			
0.34	377.0	596	633	400	660	10.5
0.35	354.0	576	615			
0.36	333.0	558	598			
0.37	313.0	540	582			
0.38	296.0	523	566			
0.39	280.0	508	552			
0.40	265.0	493	538	330	545	8.3
0.41	250.0	478	524			
0.42	237.0	464	512			
0.43	226.0	452	501			
0.44	214.0	438	488			
0.45	204.0	427	478			
0.46	194.0	415	468			
0.47	185.0	405	458			
0.48	176.0	394	448			
0.49	168.1	383	439			
0.50	160.8	373	431			
0.51	152.6	362	422			
0.52	145.9	353	413			
0.53	139.7	344	406	230	380	7.05
0.54	133.5	335	398			
0.55	127.7	327	391			
0.56	122.4	318	384			
0.57	116.8	310	377			
0.58	111.8	302	371			
0.59	107.6	295	365			
0.60	102.8	287	359			

*With welder electrodes shorted

TABLE 22. WELDER CAPACITOR-UNIT DATA, 460-VOLT 60-CYCLE LINE

Welder power factor	Capacitor ohms (per one welder kva) for unity power factor	Capacitor volts during weld	Welder primary volts during weld	Required capacitor		
				Capacitor continuous voltage rating	Maximum permissible short-circuit capacitor volts	Ohms per capacitor unit
(1)	(2)	(3)	(4)	(5)	(6)*	(7)
0.25	3,070	1,722	1,780	1,150	1,900	88.3
0.26	2,830	1,652	1,712			
0.27	2,615	1,589	1,650			
0.28	2,430	1,526	1,590			
0.29	2,250	1,470	1,535	1,000	1,650	66.2
0.30	2,100	1,414	1,482			
0.31	1,955	1,362	1,435			
0.32	1,832	1,318	1,390	895	1,478	53.0
0.33	1,716	1,272	1,349			
0.34	1,613	1,231	1,309			
0.35	1,516	1,191	1,271	815	1,345	44.2
0.36	1,422	1,150	1,236			
0.37	1,343	1,118	1,202	750	1,238	38.0
0.38	1,267	1,081	1,171			
0.39	1,200	1,051	1,141	705	1,164	33.1
0.40	1,136	1,020	1,112			
0.41	1,074	990	1,085	660	1,090	29.4
0.42	1,017	962	1,059			
0.43	965	933	1,035			
0.44	919	908	1,011			
0.45	874	844	989			
0.46	830	859	968	575	948	22.0
0.47	791	835	947			
0.48	756	815	928			
0.49	719	792	908			
0.50	686	771	890	515	850	17.7
0.51	656	751	873			
0.52	627	731	855			
0.53	598	713	840	485	800	15.5
0.54	572	694	824			
0.55	544	676	809	460	758	14.0
0.56	523	658	795			
0.57	502	643	782			
0.58	480	626	768	425	700	12.0
0.59	459	609	754			

TABLE 23. WELDER CAPACITOR-UNIT DATA, 575-VOLT LINE

Welder power factor	Capacitor ohms (per one welder kva) for unity power factor	Capacitor volts during weld	Welder primary volts during weld	Required capacitor		
				Capacitor continuous voltage rating	Maximum permissible short-circuit capacitor volts	Ohms per capacitor unit
(1)	(2)	(3)	(4)	(5)	(6)*	(7)
0.25	4,860	2,170	2,240	1,630	2,690	177.0
0.26	4,470	2,075	2,150			
0 27	4,140	1,993	2,070			
0 28	3,840	1,920	2,000	1,320	2,180	118.0
0.29	3,570	1,848	1,930			
0.30	3,320	1,780	1,866			
0 31	3,100	1,715	1,806	1,150	1,900	88.3
0.32	2,890	1,657	1,750			
0 33	2,710	1,600	1,696			
0 34	2,550	1,548	1,646			
0.35	2,390	1,497	1,600	1,000	1,650	66.2
0.36	2,250	1,450	1,555			
0.37	2,130	1,406	1,513			
0.38	2,010	1,363	1,474			
0.39	1,898	1,322	1,435	895	1,478	53.0
0.40	1,798	1,283	1,400			
0.41	1,699	1,245	1,366			
0.42	1,616	1,212	1,334	815	1,345	44.2
0.43	1,530	1,175	1,303			
0.44	1,456	1,144	1,272			
0.45	1,385	1,112	1,244	750	1,238	38.0
0.46	1,311	1,078	1,216			
0.47	1,258	1,055	1,192	705	1,164	33.1
0.48	1,196	1,023	1,166			
0.49	1,140	997	1,143			
0.50	1,086	970	1,120	660	1,090	29.4
0.51	1,034	942	1,097			
0.52	990	920	1,077			
0.53	945	895	1,056			
0.54	903	872	1,037			
0.55	865	850	1,018	575	948	22.0
0.56	828	828	1,000			
0.57	792	807	983			
0.58	760	787	966			
0.59	726	766	949	515	850	17.7

Referring to Table 21, at a power factor of 0.42, column 1, it is seen under column 2 that the required capacitor ohms for unity power factor equal 237 per welder kva. Since the welder kva is 350 the capacitor ohms are obtained by dividing 237 by 350, which gives 0.677 ohm.

Column 3 shows that the capacitor voltage during weld is 464. Since it is impracticable to build a capacitor for every small step in voltage, it is necessary to limit ratings to steps that are conveniently obtained. Therefore, certain capacitor voltage ratings are used over a limited range. This example falls within the range of a capacitor that would have a continuous rating of 330 volts (column 5) and a during-weld voltage up to 150 per cent of 330, 495 volts.

A 330-volt capacitor has a reactance of 8.3 ohms, as shown under column 7. A sufficient number of such capacitors must therefore be used to obtain the desired reactance of 0.677 ohm. Or,

$$\frac{8.3}{0.677} = 12.26$$

Round out the number of capacitor units to the next whole number, or 13. This number will make the power factor slightly lagging, rather than allowing it to lead.

Column 4 shows that the welder primary must be rewound for 512 volts.

Column 6 gives the maximum permissible voltage that may be allowed to appear on the series capacitor. A check must be made to determine whether this limit will be exceeded when, for example, the welder electrodes are allowed to come into direct contact.

Using the figures for the requirements of columns 3 and 4 in the foregoing example, the maximum permissible voltage may be determined as follows:

Z_{wsc} = welder short-circuit impedance.
R_{wsc} = welder short-circuit resistance.
X_{wsc} = welder short-circuit reactance.
$Z_{wsc} = E^2$ (column 4) $\div$ (kva $\times 10^3) = 512^2 \div (450 \times 10^3)$
$= 0.582$ ohm.
$R_{wsc} = 0.582 \times 36$ per cent power factor $= 0.209$ ohm.
$X_{wsc} = \sqrt{0.582^2 - 0.209^2} = 0.543$ ohm.
Net reactance $= X_C - X_{wsc} = 0.677 - 0.543 = 0.135$ ohm.
X_C = reactance ohms of the series capacitor previously determined.
X_1 = welder short-circuit net reactance determined above.

Net impedance $= \sqrt{R^2_{wsc} + X_1^2} = \sqrt{0.209^2 + 0.135^2} = 0.249.$
Line current $= (E - \text{tube drop}) \div Z = (230 - 15) \div 0.249$
$= 863$ amp.
Capacitor voltage $= X_C \times 863 = 0.677 \times 863$
$= 582$ volts (shorted electrodes).

NOTE: No allowance is made here for drop in line voltage due to regulation. This should be taken into account in specific cases.

In this instance the capacitor voltage reaches 582, whereas the permissible value shown under column 6, Table 21, is 545 volts. This means that the voltage must be limited by some protective device or that a capacitor must be selected with a higher continuous rating.

If a higher voltage capacitor is selected, more units will be required. A 400-volt capacitor has a permissible voltage of 660, which is ample here. Such a unit has 10.5 ohms. Since substantially a 0.677-ohm X_C total is required, the number of 400-volt capacitors needed is obtained by dividing 10.5 by 0.677, which gives 15.5 capacitor units. This may be rounded out to 16 units.

It is often more economical to use a slightly larger number of units in cases where the capacitor voltage limit is exceeded under these conditions, rather than to add accessory devices to protect the capacitor.

With a seam welder it is always desirable to select the capacitor for the voltage developed when the electrodes are shorted, rather than use additional protective devices, because the electrodes will frequently come in contact during welding operation. Protective devices would interfere with the normal use of the welder.

The example just discussed assumes that the welder will be rewound to use a series capacitor or that a new correctly wound welder is being considered. This arrangement is shown in more complete detail in Fig. 119. If the welder is to remain unchanged, a transformer may be designed to go ahead of it, as shown in Fig. 117. Then the initial values of kva and power factor during weld and the kva and power factor when the electrodes are shorted must be applicable to the transformer plus the welder. The procedure is the same as described. The input side of the transformer is given under column 4 and the low side is the welder voltage rating minus the tube drop, which is 15 volts.

If the series capacitor is to be located as shown in Fig. 118 its voltage rating will be lower, and may be computed using the tables, as follows:

Kva of welder during weld = 350.
Power factor during weld = 42 per cent.
Welder rating = 230 volts (to remain unchanged).

Referring to Table 21, column 2, it will be seen that 237 capacitor ohms are required per welder kva. With 350 kva this gives 0.677 ohm total.

This value of 0.677 ohm assumes that the welder will be rewound for 512 volts, as shown in column 4, but since this is now not the case, adjustment must be made for the voltage change, and the capacitor ohms reduced by the square of the voltage. That is,

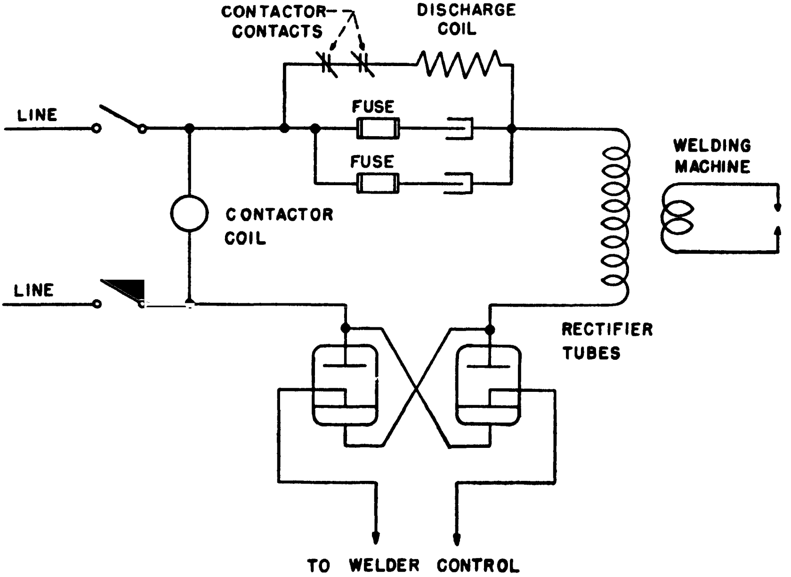


FIG. 119. Use of a series capacitor when a welder is wound for the correct voltage to operate with a series capacitor.

$$\frac{512^2}{(230 - 15)^2} = 5.67$$

$$\frac{0.677}{5.67} = 0.12 \text{ ohm}$$

The current flowing through this capacitor during weld will be determined by the kva and the welder operating voltage. Or,

$$(350 \times 10^3)/215 = 1{,}630 \text{ amp}$$

The voltage on the capacitor during weld is

$$1{,}630 \times 0.12 = 195 \text{ volts}$$

By inspecting Tables 21, 22, or 23, column 3, a capacitor can be selected whose during-weld operating range includes 195 volts. A 230-volt capacitor fulfills this requirement. Since a 230-volt capacitor has a reactance of 7.05 ohms, the total number of such capacitors required is

$$\frac{7.05}{0.12} = 58.8$$

Here is an excellent example of the objection to using a transformer on the line side of the series capacitor. A total X_C ohms, or 0.12, is needed for a during-weld voltage of only 195, thus making it necessary to use 230-volt units and operate them well below their rating.

It is not practicable to build a capacitor with less dielectric than used in a 230-volt rating, with the result that 59 units are required to obtain the low value of ohms needed. For this reason the arrangement used in Fig. 113 should never be considered for a welder designed for 230 volts. With welders designed for 460 volts or higher the arrangement shown in Fig. 118 may be practicable, and is often used to keep down the voltage on the tubes.

Welder circuits using series capacitors are less subject to the transients usually encountered with nonsynchronous switching, as, for example, with magnetic contactors. Welds are therefore more consistent with this arrangement.

Where synchronous electronic control is used it is necessary that the capacitor be charged to peak value and that this charge be maintained between welds.

SUMMARY OF ADVANTAGES

The advantages of series capacitors may be summarized as follows:

1. Voltage dips may be reduced and lamp flicker eliminated.
2. Interference of one welder with other welders may be eliminated.
3. Adjustments in welders are easier due to improvement of regulation.
4. Heavier welds are possible on a given power supply.
5. Welders may be installed on feeders which are not otherwise able to handle the low-power-factor welders.

Bibliography

A.I.E.E. COMMITTEE ON ELECTRIC WELDING, Power Supply for Resistance Welding Machines, A.I.E.E. Winter Convention, New York, Jan. 22–26, 1940.

LEVOY, L. G., JR.: Power Factor Correction of Resistance Welding Machines, A.I.E.E. Winter Convention, New York, Jan. 22–26, 1940.

PONKOW, J. E., and N. A. SMITH: Capacitors Aid Resistance Welders, *Westinghouse Engineer*, March, 1944.

CHAPTER 10

CAPACITOR INSTALLATION AND MAINTENANCE

INSTALLATION OF CAPACITORS

Shunt capacitors are usually installed in one of two ways. Outdoor-type capacitor units are mounted and connected for operation exposed to the weather. Indoor-type capacitor units are supplied for use in housings which protect them from the weather, and enclose all live parts. Often the circuit breaker is installed in this same housing.

The outdoor-type units must be mounted in a manner that will permit free circulation of air between the units. They are usually rated for 46°C ambient temperature; however, this rating is based upon the condition that they be mounted to have unrestricted air circulation, and not under the roof of a building where the air movement is poor and the capacitor may be subjected to radiation from the roof. It is important that care be taken to follow manufacturers' recommendations, particularly if the mounting racks are not supplied with the capacitor units but are constructed on the job. Multi-tier assemblies of outdoor capacitor units must not be operated up to the same high ambient temperatures as single-tier installations. Some unit ratings in kva may carry lower or higher ambient limits. In any case where it is evident that the ambient temperature limits set by the manufacturers are likely to be exceeded, this fact should be called to their attention and consideration given to the use of capacitor units specially designed or rated for these high temperatures. Forced ventilation of housed capacitors may be the answer when the ambient temperature is above the limits assumed for standard housed equipments.

FUSES

In selecting fuses for use with capacitor banks it should be recognized that a fuse cannot protect a capacitor as it does a motor. An overloaded motor may be protected by the blowing of a fuse but a capacitor load depends on applied voltage.

The load on a capacitor is measured in operating kvar and this varies as the square of the voltage, neglecting harmonics. It would be impossible to select a fuse that would protect the capacitor against overvoltage because such a fuse would blow on energizing the capacitor. Fuses on capacitors are used primarily to remove a short-circuited capacitor from the circuit and thus protect the circuit from a prolonged outage. Fuses are also used to remove a faulty capacitor out of a group of capacitors so as to keep the remaining capacitors in service. Another advantage of a fuse is to help locate the faulty capacitor so as to eliminate the need of testing all of the capacitors in a group in order to locate the faulty one.

When individual capacitor-unit fuses are used they are chosen with a rating which will permit them to handle the switching current transients likely to be encountered when the capacitors are energized or deenergized, or when the capacitors are suddenly discharged into a shorted capacitor.

Where fuses are to be selected for a group of capacitor units—as, for example, the three-fuse cutouts for a 180-kva pole-mounted bank of outdoor units—the rating of the fuse should not be less than 165 per cent of the normal continuous capacitor current. Individual unit fuses are of low current rating and have less thermal capacity and their rating must be two to five times the normal capacitor current.

INSTALLATION CHECKUP

The first important operating condition to be considered is the voltage. Most capacitors are rated on the basis that the average voltage over any 24-hr period will not exceed the rated voltage by more than 5 per cent. The voltage may reach 110 per cent of rated voltage for short periods as long as the average limit of 105 per cent is not exceeded.

Where there is any doubt regarding the voltage a recording volt meter should be used over a sufficient period of time to establish the average operating voltage.

The operating voltage often exceeds permissible limits during light loads, when the capacitor is usually not needed. When this is so a simple solution is to equip the capacitor with suitable relays and accessories so that it will be automatically disconnected when the voltage exceeds some predetermined limit for a prolonged period of time.

If the capacitor is allowed to operate at excess voltage its life may be reduced due to the thermal overload resulting from excess operating kvar. During high ambient temperature, as in the summer, the operating temperature of the capacitor may be in the unstable range and the loss of some capacitor units may be the result.

If the capacitor is known to be operating at excess voltage, the capacitor-unit case temperature should be watched carefully until the condition is corrected. When the case temperature exceeds 85°C there is likelihood of the heat damaging the capacitor. Capacitors may, however, be damaged by voltage alone, even though excess temperatures are not attained.

The next check to be made is on the current being drawn by the capacitor. Since the capacitors are usually purchased on the basis of kvar and voltage, it is a simple matter to calculate the expected current.

$$I = \frac{\text{kvar} \times 10^3}{\text{voltage} \times \sqrt{3}} = \text{phase current}$$

The measured current may be higher than this indicated current for two reasons. The manufacturing tolerance used for power capacitors is minus zero plus 15 per cent. It is not to be assumed that all units will ever be 15 per cent high although this is theoretically possible. Actually they will average 6 or 7 per cent high. A tolerance of 0 + 15 per cent is used to insure that the required manufacturing variations will all be in the range above the rating and a capacitor having a given rating in kvar will always be equal or more than this value. As pointed out, one should not be surprised if the measured current is 6 or 7 per cent higher than the indicated value.

Another reason for the current being higher is that no voltage wave is perfect. There is always some departure from a perfect sine wave. In other words harmonics are always present. Harmonic voltages having frequencies higher than the rated frequency will cause additional current of flow, in an amount depending on the harmonic voltages and harmonic frequencies.

The rms voltage as measured in this case will be the square root of the sum of the squares of the fundamental and harmonic voltages. For example, let us assume that the fundamental frequency is 60 cycles and designate the voltage at this frequency as V_{H1}. Also assume that there is present a small 180-cycle, or third-harmonic, voltage and some voltage at the fifth harmonic. These 180-cycle and 300-cycle voltages will be designated as V_{H2} and V_{H2}. The measured rms voltage is expressed as

$$\text{Rms volts} = \sqrt{(V_{H1})^2 + (V_{H2})^2 + (V_{H3})^2}$$

The impedance of a capacitor varies with frequency. To determine the capacitor kvar it is necessary to calculate the kvar for each harmonic voltage as

$$\text{Kvar} = \frac{E^2 2\pi fc \times 10^{-6}}{1{,}000}$$

This makes it necessary to know the harmonic voltages. Measuring the harmonic voltages is a difficult procedure.

Most standard capacitor equipments are designed to permit operation up to 135 per cent of rated kvar, this 35 per cent being made up of overvoltage at the fundamental frequency up to 105 per cent voltage, plus additional kvar due to harmonics.

When a capacitor installation is being checked and it is found that the current is in excess of the value which would be expected from the rated voltage and kvar, there are three steps that can be taken to determine if the capacitor is being operated beyond safe limits, or to determine if the above thermal limit of 135 per cent is being exceeded. These steps are as follows:

1. *Rough Check.* Measure rms voltage and current and use these figures to calculate the kvar. If the figure so obtained is within 135 per cent of the rated kvar and if the rms voltage is not more than 105 per cent of rating, one can be sure that the 135 per cent kvar limit is not being exceeded because no account is taken of the reduced impedance of the capacitor at higher frequencies. If this check gives a value greater than 135 per cent it is necessary to make the second check.

2. *Second Check.* Observe the voltage with an oscillograph so as to determine which harmonic predominates, such as third, fifth, or seventh. Use the curves of Fig. 12, Chapter 2, in selecting the curve corresponding to the predominating harmonic. This will give the permissible current. If this check indicates that the 135 per cent thermal limit is being exceeded it is necessary to make the third check.

3. *Third Check.* Measure the harmonic voltages separately with a harmonic analyzer and calculate the capacitor kvar at the fundamental and at each harmonic, and add these values to obtain the total actual operating kvar. This should not exceed the rated kvar by more than 35 per cent.

If the harmonic currents are sufficient to result in operation of the capacitor in excess of 135 per cent kvar, as explained above, one or more of the following remedies should be considered.

1. Relocation of part or all of the capacitors to other parts of the circuit may reduce overcurrent due to partial resonance, by changing the circuit constants.
2. Capacitors may be switched off the circuit during periods in which overcurrents are likely to occur. Automatic control actuated by change in current, change in voltage, change in reactive kva, or by time clock may be used.

3. If solutions 1 and 2 are not applicable, it will be necessary to add inductance in the circuit to make the capacitor resonant to a frequency higher than the predominating harmonic, or to insert a filter ahead of the capacitor to introduce impedance at the particular troublesome frequency.

When series reactors are used it must be noted that they produce a boost in the voltage on the capacitor by an amount equal to the capacitor current times the reactance ohms. Unless special rated capacitors are used, the use of reactance is limited to relatively small amounts, such as a few per cent, if one is to leave an adequate margin between the capacitor average operating voltage and the maximum permissible operating voltage.

Filters are sometimes used because the needed high impedance to the harmonic can thus be obtained with a minimum boost in the 60-cycle voltage on the capacitor.

Other tests may be required after installation, if the capacitor is equipped with automatic switching, to determine if the switching operations are taking place corresponding to the right conditions of circuit voltage, or for the right plant-load conditions.

The ventilation should be checked to make sure it is unobstructed.

TESTS ON CAPACITOR UNITS

It is generally unnecessary to make field tests on capacitor units when they are new and before placing them in service. It is also unnecessary to make periodic tests on units during service to note evidence of slow change or deterioration, because capacitors are well sealed and experience shows that they do not change in a manner that can be detected by tests on the complete capacitor unit. When a capacitor unit fails in a bank of capacitors and the case of the faulty unit is ruptured, the disturbance may be quite general and arcs may play between points in the housing, subjecting several units to damage either externally or internally. When such cases are encountered, usually on rare occasions, it is not always possible to select the damaged capacitor units without making a few simple tests.

The field tests on capacitor units to establish serviceability are as follows:

1. Capacitance test.
2. Voltage test.
3. Fluid-leak test.
4. Internal-discharge test.

1. **Capacitance Test.** The capacitance may be checked with sufficient accuracy by simply measuring the current drawn, using a known voltage and frequency. The result can be obtained in kvar as

$$\text{Kvar} = \frac{\text{rms voltage} \times \text{rms current}}{1{,}000}$$

The kvar rating of the capacitor can be converted into capacitance in microfarads:

$$C = \frac{\text{kvar} \times 10^3}{E^2\, 2\pi f \times 10^{-6}}\ \mu\text{f}$$

$$I = E\, 2\pi f C \times 10^{-6}\ \text{amp}$$

Allowance must be made for the manufacturer's tolerance of 0 + 15 per cent. A single 15-kvar capacitor unit may be 15 per cent over the rated kvar.

Allowance must be made for harmonics which may be present, by checking a capacitor whose capacitance in microfarads is known.

2. **Voltage Test.** The voltage test may be considered in two parts if the capacitor has two insulated terminals. The first test is between the two terminals and the case. This may be made by applying about 75 per cent of the recommended N.E.M.A. tests on new capacitors. On a 2,400-volt capacitor unit this would be about 14,000 volts. This test can be made by means of an ordinary test box since the current will be very small. This test checks the terminals as well as the internal insulation separating the working element of the capacitor from the case. The second voltage test consists of applying a voltage between the terminals of the capacitor. This test is more difficult to make and unless suitable equipment is available it is best to make it by merely applying the rated voltage. A 2,400-volt 15-kvar capacitor could be so tested by connecting the terminals of the capacitor to the 2,400-volt winding of a 15-kvar 115/230- to 2,400-volt distribution transformer with a fuse on the 115-volt side. The transformer may be energized or deenergized with the capacitor connected. The current measured in the 115-volt side corrected for transformer ratio will indicate whether the capacitor is normal. The capacitor will either draw no current, indicating open connection; or it will draw double current, indicating one group of sections are shorted out; or it will draw a normal current within the limits of 0 + 15 per cent.

With suitable equipment to apply rated voltage, raise to test value, and lower to rated voltage, the tests may be about 75 per cent of

N.E.M.A. recommended tests for new capacitors. In the case of a 15-kva 2,400-volt capacitor this would be about 3,750 volts.

If the capacitor case forms one terminal this is the only type of voltage test that can be made.

3. Tests for Leaks. Sometimes a capacitor in service may develop a leak and several units may be coated with fluid when only one is actually leaking. The actual leak may be found by proceeding as follows:

1. Clean unit thoroughly with a good cleaner to remove all traces of fluid.
2. Place unit horizontally on a sheet of clean brown wrapping paper in an oven and allow to remain 8 hr at a temperature not exceeding 75°C.
3. Examine paper and unit surface for leaks.

4. Internal-discharge Test. The effectiveness of the internal discharge resistor may be checked by measuring the value in megohms using any resistance bridge. The value should be sufficiently low to discharge the capacitor to 50 volts in the required time, starting at the peak value of the rated rms 60-cycle voltage. The required time is 1 min for capacitors rated at 600 volts and below and 5 min for those rated above 600 volts. This is an underwriter's requirement.

$$E = E_o \times e^{-t/RC}$$

where E = voltage after time t.
E_0 = original voltage.
e = natural log base, 2.718.
R = resistance, megohms.
C = capacitance, farads.
t = time, sec.

Summary of Tests and Interpretation

1. Blowing of the fuse indicates a shorted capacitor. Arcing inside of the capacitor indicates that some of the sections are shorted. Absence of current indicates that the capacitor is open circuited.
2. Normal current or current up to 115 per cent of normal indicates that the capacitor is in good condition.
3. Current in excess of 115 per cent of normal indicates that either some of the series sections are shorted out or that there are harmonics in the supply voltage. Capacitors rated at 1,500 volts or above contain series sections. If the wave form of the test voltage is questionable, capacitors drawing an excess current

should be rechecked for capacitance on another circuit, as, for example, on a 230-volt lighting circuit, observing the voltage and current.

4. Current well below normal indicates a damaged capacitor.
5. In testing three-phase units, short one phase and test between this jumper and the other terminal. This applies tests to two-thirds of the capacitor. Repeat until three such tests are made, first shorting *A* to *B*, then *B* to *C*, and finally *A* to *C*. Expected normal current values are 66⅔ per cent of the values for a single-phase unit.

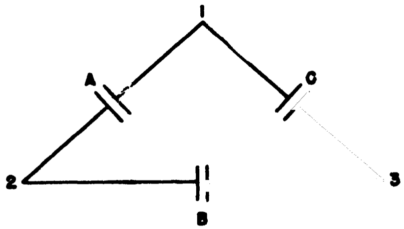


FIG. 120. Delta-connected capacitor units.

6. While it is not often needed, the actual value of capacitance in each phase of a three-phase delta-connected unit can be measured as follows:
   - *a*. Connect 1 and 2 together (Fig. 120) and test between this point and 3, using a known voltage. Calculate μf, which will be the sum of *B* and *C*.
   - *b*. Connect 1 and 3 and test to 2 to find capacitance of $A + B$.
   - *c*. Find $A + C$ in the same manner.
   - *d*. Then $A = \dfrac{(A + B) + (A + C) - (B + C)}{2}$

$$B = \frac{(A + B) + (B + C) - (A + C)}{2}$$

$$C = \frac{(A + C) - (A + B) + (B + C)}{2}$$

TYPES OF CAPACITOR UNITS

Capacitor units for a-c service are made in single-phase, two-phase, three-phase, and two-value single-phase units.

Single-phase units have two terminals with one value of capacitance. One terminal may be common to the case.

Two-phase units actually consist of two separate values with four terminals, and could be considered as two separate and equal capacitors, each having two terminal bushings.

Three-phase units are divided internally into three equal values, and are delta-connected, with three terminal bushings.

Two-value capacitors are capacitors having one value equal to 33⅓ per cent and one equal to 66⅔ per cent, with one common terminal and two alternate terminals. These are usually referred to as sectionalized capacitors.

A single-phase unit, if for 460 volts and 15 kva, would be made up of one 190-μf element assembly and would draw a current of 32.6 amp. These units are usually used in large assemblies and groups of units are delta-connected on three-phase circuits.

A 460-volt two-phase unit would consist of two 95-μf elements and draw 16.3 amp per phase.

A 460-volt three-phase unit would consist of three 63.3-μf elements and draw a phase current of 18.85 amp.

A 2,400-volt two-value, or sectionalized, unit would have one 2.3-μf element and one 4.6-μf element. Units of this type are used to permit operation on 2,400 volts delta-connected or 4,160 volts Y-connected when the total number of units is divisible by two. If divisible by three, single-phase 2,400-volt units could obviously be delta-connected on 2,400 volts and Y-connected on 4,160 volts, but this would give steps of 45, 90, and 135 kva. If steps of 30, 60, 90, and 120 kva are desired involving two, four, six, or eight units, one solution is to use three-phase units. These, however, cannot be reconnected for 4,160 volts and are objectionable because it is frequent practice to change 2,400-volt lines to 4,160 volts. The two-value unit such as previously described provides the solution.

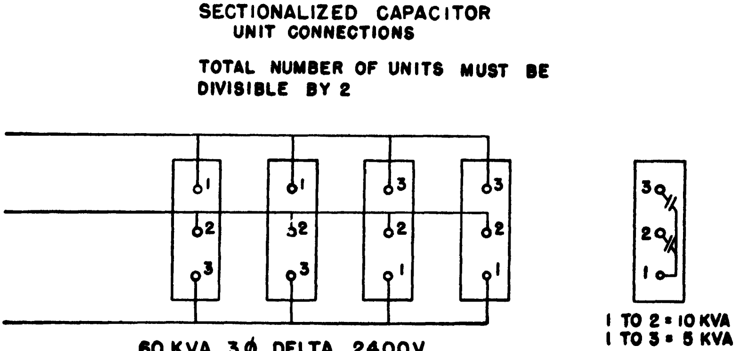
Figure 121 shows how these two-value, or sectionalized, capacitors would be connected to make up a 60-kva bank of capacitors.

SPECIAL USE OF CAPACITOR UNITS

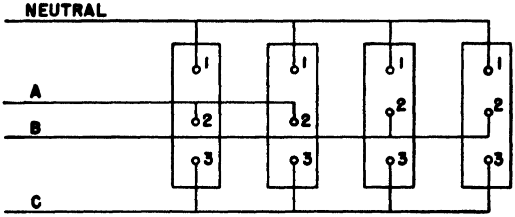
Single-phase Units. These are sometimes used in series if insulated on extra insulators or if the total voltage is within the voltage class of the bushings. Thus, two 230-volt units could be connected in series but two 460-volt units could not be without supporting each unit on insulators.

Two-phase Units. Obviously two-phase units can be used as single-phase units if the two halves are connected in parallel. The two halves of a 230-volt unit could be connected in series, making a 460-volt 7½-kva unit. The two halves of a 2,400-volt two-phase unit cannot be connected in series because this exceeds the voltage class of the bushings.

Three-phase Units. Three-phase 230-volt units can be operated in series on 460 volts if they are made up in groups of three units, as shown in Fig. 122. The total kva is 80 per cent of the rated kva, or 18 kva for three 7½-kva 230-volt units. Line voltage should not exceed 460 volts in this case.



60 KVA, 3 ϕ DELTA 2400V.
USING SECTIONALIZED UNITS
20 KVA PER PHASE, BALANCED.
(A)



60 KVA, 3 ϕ, 4160 WYE
USING SECTIONALIZED UNITS
20 KVA PER PHASE, BALANCED.
(B)

FIG. 121. Sectionalized capacitor units.

Three-phase units may be used on single phase by shorting one phase and thus obtaining 66⅔ per cent of the total kva. If connection is merely made to any two of the three terminals, the kva will only be 50 per cent.

DISCHARGING CAPACITORS

Capacitors to be installed under conditions covered by the National Electrical Code are provided with means of reducing the residual voltage in accordance with code requirements. This is usually accomplished by means of discharge resistors built into the capacitor units. Additional discharge means are sometimes used for providing more rapid discharge in cases such as that of automatically switched banks.

In some capacitor applications—as, for example, series capacitors used with resistance welders—the discharge means is external to the capacitors and connected automatically when the line switch is opened.

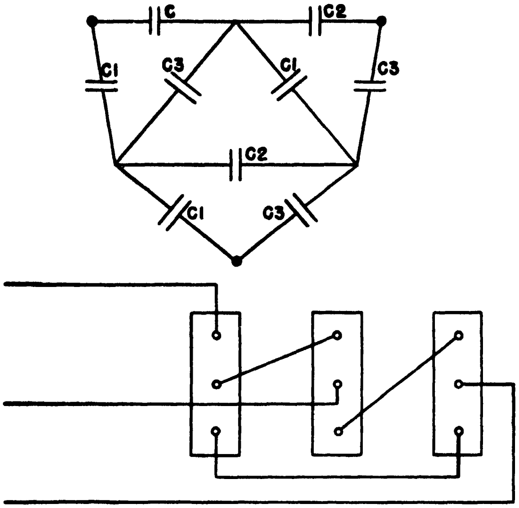


FIG. 122. Delta-connected 230-volt capacitors connected for operating on three-phase 460-volt line.

It is necessary for series capacitors to hold their charge between welding operations to avoid variable weld characteristics, so they are discharged only when the welder is disconnected from the line.

Capacitors not subject to the requirements of the National Electrical Code are provided with means of reducing the residual voltage to approximately 50 volts within 5 min after the capacitor is disconnected from the source of supply.

Capacitors which are automatically controlled should have discharge means which reduce the residual voltage to 50 volts or less between one switching operation and the next.

The use of a discharge device is in all cases intended to supplement rather than to displace the practice of short-circuiting a unit before handling.

The discharge resistor may be checked by merely measuring the value of this resistance in megohms, using direct current and a microammeter.

The voltage which an a-c capacitor retains after being disconnected from its circuit is equal to the peak voltage applied to its terminals immediately before the circuit interruption, since the capacitor current leads the capacitor voltage by 90 deg and a-c current interrupters operate to open the circuit at a current zero.

One phase of a delta-connected capacitor bank will retain a peak line-to-line voltage charge when the bank is removed from the line, while the two remaining phases will be charged to one-half this voltage. A grounded Y-connected bank will retain a peak line-to-neutral voltage charge on each phase. However, in the event the bank is not grounded, two of these phases will be charged only to one-half of peak line-to-line voltage. This analysis of the voltage retained by capacitors after removal from the line is theoretically accurate and will be found to apply in the vast majority of capacitor-switching operations, regardless of the type of circuit interrupter employed. It should be assumed to apply in every instance since it represents the worst possible conditions so far as energy storage and resulting dangers to operating personnel are concerned.

Electrical energy, W, in watt-seconds, stored by a 60-cycle capacitor bank upon interruption of operation at its rated voltage is given by

$$W = 2.65 \text{ kvar}$$

for single-phase and grounded Y-connected banks, where the kva referred to is the total rated kva of the bank. For an ungrounded Y-connected bank the stored energy will be 83.5 per cent and for a delta-connected bank 50 per cent of that given by this equation. The smaller quantities of energy stored by these two types of banks result from the retention of a voltage charge of less than peak rated voltage by two of the phases, as stated above. The total energy stored by the bank will be distributed among the phases in such a way that the percentage of the total energy stored by a given phase is proportional to the square of the voltage retained by that phase.

The built-in discharge device is merely a resistor of stable design, connected in parallel to the capacitor sections. The value of this resistor is usually made such that the voltage after a given time will not exceed 50 volts. All capacitors rated at or below 600 volts must be discharged in 1 min to 50 volts, while for others the time is 5 min.

INDEX

A

Absorption, dielectric, 2
Analysis of circuit conditions, 140

B

Boost in voltage due to capacitors, 82, 83
Breakers, circuit, 118, 119, 151
Bushings, porcelain, 39

C

Calculation of voltage drop, 98, 99, 100
Capacitance, change of, with temperature, 13, 14, 17, 18, 19
Capacitors, castor-oil-impregnated, 56
  characteristics of, 13, 14, 15, 17, 18, 19
  construction of, 34, 35, 36, 37
  design calculations of, 33, 34
  directly connected to motors, 73, 84, 85, 86
  energy-storage type of, 58
  losses in, 9, 10, 15, 18, 19
  mineral-oil-impregnated, 3, 5, 9, 11, 12, 13, 14, 16
  pentachlorodiphenyl, 56
  series-connected units of, 51
  switched in parallel, 125, 126, 127, 128
  tests for, 44
  unit ratings of, 22, 23, 24
  for X-ray application, 59, 61
  water-cooled type of, 52, 53
Castor oil, impregnant, 9
Chlorinated aromatic hydrocarbons, 9
Chlorinated diphenyl, 10, 12, 13, 16
Chlorinated naphthalene, 9
Compensation, line reactance, 155
  of load reactance, 178, 179
Control, automatic, 133
  methods for, 134, 135
  type of, required, 135
Corrosion protection, 41
Crossarm mounted capacitors, 51
Current, inrush, 120, 121, 122, 123, 124

D

Deenergizing transient, 131
Demand charges, 76
Dielectric, polar, 1
Dielectric absorption, 2
Dielectric constant, 1, 2, 4
Dielectric loss, 10, 15, 19
Dielectric polarization, 1, 2
Direct current, capacitors for, 55, 56
  power capacitors for, 57
Discharge resistors, 42, 44
Dissipation factor, 16

E

Economic gains, 105
Electrostatic energy, 1
Enclosed capacitors, 46
Energy charge affected by kva demand, 77
Energy-storage capacitors, 58
Energy-storage welding, 60, 61

F

Ferroresonance, 167
Finish, zinc-sprayed, 41, 42
Flash photography, application of, 60
Foil, aluminum, 8
  in capacitors, 31
Frequency, 26
  of inrush current, 123, 124, 128, 129
Fuses, bank, 113, 114
  individual capacitor-unit, 5, 113

G

Gasket-sealed terminals, 39
Generator, capacity of, increased, 108

H

Harmonics, 26
Hermetic seals, 39
High frequency, 51, 52, 53
Housed capacitors, 49

I

Impregnants, castor-oil, 9
  chlorinated-diphenyl, 10, 12, 13, 16
  chlorinated-naphthalene, 9
  mineral-oil, 3, 5, 9, 11, 12, 13, 14, 16
Indoor capacitors, 43, 48
Induction furnace, power factors in, 68
Industrial load, power factors in, 66
Inrush currents, 120, 121, 122, 123, 124
Instantaneous kva demand charge, 179
Intermittent duty, 29

K

Kilowatt gains in line capacity, 93
Kvar sensitive relay, 144

L

Limiting of inrush current, 131
Line, increase capacity of, with capacitors, 108
Line-reactance compensation, 155
Load, light, causing overvoltage, 81
  reactance-compensation, 178
Load power factor, variations in, effect on voltage, 96
  effect on transformer regulation, 71
  industrial, 66
Location, of shunt capacitors, 72, 101
  of series capacitors, 158

M

Metallic band on porcelain, 39
Mineral oil, characteristics of, 13, 15
  impregnant, 3, 5, 9, 11, 12, 13, 14, 16
Motor power factor, 67, 78

O

Outdoor capacitors, 43, 50, 89, 190
Overcompensation with series capacitors, 163
Overvoltage during light loads, 81

P

Paper, used in capacitors, 31
  conducting articles in, 5, 30
  density of, 31
  of linen, 5
  porosity of, 30
  wood-pulp, 5
Pentachlorodiphenyl, characteristics of, 14, 15, 16, 17, 18, 19
  impregnant, 13, 16
Polarization, atomic, 1
  dipole, 1
  electronic, 1
  interfacial, 2
Pole, crossarm-mounted capacitors on, 51
Porcelain, bushings of, 39
  firing metallic band on, 40
  mounting of, on capacitor, 41
  tests for, 44
  tinning metallic band on, 40
Power, active, 65
  apparent, 65
  rates for, 74
Power factor, 64
Power-factor clauses, 75
Pressure, assembly, 34
Processing capacitors, 37
Protection, against corrosion, 41
  against surges, 60, 62, 63

R

Rates, electric power, 74
Reactive factor, 65
Reactive power, 65
Reduced voltage, effect on motor performance of, 69
Reduction, in instantaneous kva demand, 74
  in kva demand, 76
  in line losses, 89, 91, 106
Released substation capacity, 107
Residual voltage, 42
Resonance, subsynchronous, 175, 176

S

Self-excitation of motors, 84, 85, 86, 176, 177
Series, capacitors in, 155, 178
  connected capacitor units in, 116
Series-capacitor protective methods, 158
Series parallel, connected units in, 51
Service, d-c, 55, 56, 57
Shunt capacitors, 71, 72
Soldered porcelain terminals, 39
Steps in switching capacitors, 135, 136
Stress, voltage, 33
Surge protection with capacitors, 60, 62, 63
Switches, for capacitors, 118, 151
  ratings required in, 118, 119
Switching, automatic, 94, 130, 131, 133
  in response to current, 138
  in response to kvar of load, 138
  in response to voltage, 136
  steps required in, 135, 136
Synthetic liquid impregnants, 3, 9, 10

T

Temperature, limits of, ambient, 26, 28
  rise of, on capacitors, 10
Terminals, 39
Testing capacitors, 44
Time-delay relays, 146
Type, of indoor capacitors, 43, 48
  of outdoor capacitors, 89

U

Unbalanced voltages on capacitor phases, 115

V

Voltage, average of, over 24 hr, 24
  boost of, due to capacitors, 82, 83, 101, 102
  continuous working, 24
  stress on, 6, 7, 9, 10
  variations in, due to load power factor, 96
Voltage-sensitive relays, 143

W

Water-cooled capacitors, 52, 53
Wave-form distortion, effect on capacitors, 192
Wax capacitors, 3, 9
Welders, power factor of, 68

X

X-ray capacitors, 59, 61
X-Wax, 11, 12

Y

Y-connected capacitators, 114

Z

Zinc finish, spraying of, 41, 42